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Preventing False Trips of Zone 3 Protection Relays in Smart Grid

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Abstract: While remote zone 3 protection relays are essential to power systems, their false trips are also one of main causes related to cascading blackouts. Although many methods have been developed on traditional power systems to address this issue, the past cascading failure events showed the ineffectiveness of these methods. With the development of Smart Grid (SG), new agent-based methods have been proposed to address this issue by utilizing SG real-time communications. We found that these solutions simply assume ideal communication networks and do not consider the effect of practical network constraints and resource management. In this paper, we propose several solutions to address practical network resource management and constraints, and further improve the agent-based solutions in order to prevent the false tripping of zone 3 relays in various conditions. We also analyze the potential issues of these solutions, and point out the future investigation in this direction.

Key words: zone 3 relay; cascading failure; real-time communications; smart grid

1 Introduction

As device failures due to aging, natural disasters, or malicious attacks can cause serious damages to power system components and transmission lines, and generate large disturbances across the systems, current power transmission systems use various local relays and remote relays to isolate such failures and prevent disturbances from wide spreading. Among these protection devices, directional relays (especially remote zone 3 relays) are essential to transmission lines for remote backup and broadly deployed in current systems[1, 2]. However, over-sensitive remote zone 3 relays caused certain unexpected trips and further spread cascading failures in many cases[3, 4]. In this paper, we focus on this critical issue to prevent such false trips.

Although many solutions have been developed on traditional power systems to address this issue[5–7], they failed to completely eliminate the problems. As shown in recent large scale failures[3], these solutions did not stop the cascading failures due to remote relay failures in many cases.

The recent fast development of Smart Grid (SG) provides us new opportunities to address these issues more accurately and effectively. In SG, intelligent power devices are connected with communication networks and support real-time monitoring and control across wide areas. Such real-time communication capability enables us to achieve more intelligent, effective, and precise control of power systems. Although several agent-based solutions[8, 9] have been proposed to utilize SG communications to deal with the false trips of zone 3 relays, they do not consider the practical network issues and simply assume dedicated communication paths in ideal network conditions, which may not be true in practice due to many potential issues, e.g., routers or links errors, misconfigurations, or network attacks, often disrupt dedicated communication paths. Especially, more and more new SG control and monitoring applications and services will be deployed across large areas for efficiency, reliability, and protection[10–13]. They often also demand high data rates and lower latency (e.g., emerging PMU operations[12])

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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 assign and manage communication network resources to support the operations of many SG applications.

In this paper, we propose several methods to improve the performance of zone 3 relay protection and then discuss the potential issues under practical network conditions. As we become more dependent on power systems, the reliability of power system becomes even more critical. Existing agent-based solutions assume dedicated network paths between agents and a master agent under ideal conditions for monitoring and control actions. For achieving a higher reliability than the existing solutions, we first present a static reservation scheme and then improve it with smart reservation and backup paths to deal with network failures. Even though such path failures may be not often, it still could generate a significant impact on zone 3 relay management. More importantly, the proposed network management solutions are applicable to many other real-time control and monitoring systems, not limited to zone 3 protection only.

The remainder of this paper is organized as follows. We discuss related work in Section 2 and introduce the analysis of existing schemes and present new solutions in Section 3. We then evaluate the proposed solutions and show their effectiveness in Section 4 and conclude this paper and discuss future investigation in Section 5.

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 wait for 0.3 s, and a zone 3 protection may wait up to 1 s[8, 9].

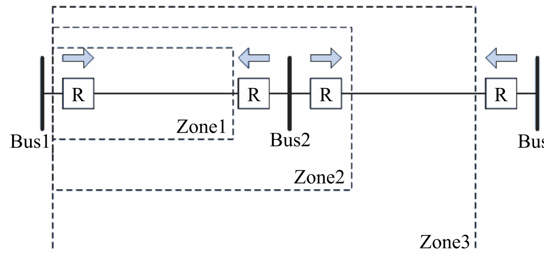


Fig. 1 Distance protection relays: zone 1, zone 2, and zone 3[9].

Hidden failures have been considered one of the main sources of large scale disturbances[3, 5, 14]. 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[15]. 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, 16–18]. One key difference between the SG and the traditional power systems is that SG enables two-way power transmission with intelligent devices that exploits 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., PMU technology[12].

Agent-based 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, as we discussed in the next section, 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 of 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 Improving the Agent-Based Solutions

In this section, we first present a simple reservation-based solution to address the concrete network resource management for the agent-based solutions, as the baseline study. We then propose a smart scheme based on the realistic failure cases. Moreover, we consider the *reliability* and *scalability* limitations under practical network conditions (such as relay errors and communication link failures), and propose our solutions to address these limitations using backup paths.

3.1 Basic network resource management for agent-based schemes

The proposed agent-based schemes[8, 9] do not consider potential issues in communication networks and simply assume that a network will deliver each message (with the TCP protocol) on a dedicated network path in the query-response process. It works if the communication network only supports the message exchange for zone 3 protection and little other traffic is transmitted on the same network. This is usually not true in practice, because a lot of other control and monitoring traffic shares the communication network in real-world deployments[12, 16, 17].

We first illustrate a basic solution to reserve network bandwidth for each application similar to existing network solutions[19]. Note that zone 3 protection is only one of them. As network errors may occur on the reserved paths, we further improve the reliability with (partially) disjoint backup paths to ensure the success of the query response process. In the following, we will first present how to perform such reservations and then discuss its limitation and potential improvement.

3.1.1 Basic management scheme

To address the potential network congestion issues, we use a basic bandwidth reservation method. Given a network, we first determine where we should put the MA on a network and then figure out the corresponding reservations on each communication link for each zone 3 protection relay.

Communication network topology and MA location. There are different methods to build the communication network for an SG, e.g., using power-line communications or long range radio links, or using common Internet cables and routers to build a network along the power lines. As power-line communications or radio links usually have long delays and low bandwidth, they may work for traditional low-demanding applications but are not fit for strict real-time applications. Therefore, the communication network of SG is usually built with common Internet devices and has the similar topology as the power network. In this paper, as many other previous projects[9], we assume the communication network have the same topology as the power transmission network.

We use the following basic procedure to define the communication network based on a given power network topology, e.g., IEEE 39-bus system. For a given power system, assume we have a power exchange bus in each substation. We use B to denote the entire set of buses for a power transmission network. Then, we sort the buses in B based on their hop counts to the MA in a decreasing order. For bus $b \in B$, we identify the set of power transmission lines L_b that connect b with other buses; for power line $l \in L_b$, we then find the set of relays R_l associated with this line, including both primary and backup relays.

Given the topology of communication network, we first need to determine where the MA should be located on the topology and then figure out the bandwidth reservations on each network link for protection relays. Many factors may affect the choice of the MA location, e.g., it should be close to a major power plant (or station). In this paper, we use a hop-distance heuristic to locate the MA at approximately the center of the topology. In other word, when we build a spanning tree of the topology with the MA as the root, the tree should have the minimum height. Using the Dijkstra's shortest path algorithm with the MA as the root and assume that all links have the same weight, we construct the shortest path from the MA to each power bus and its associated protection relays. Furthermore, as we know the delay requirement from a relay to the MA, we can then reserve bandwidth on each network link along the path for ensuring delay requirements of zone 3 protection relays. For easy of illustration, we assume all links have the identical capacity as in the previous work[8, 9].

In the following, we present how to reserve bandwidth on the communication network for relays.

Determination of the delay requirement for each relay. In an agent-based protection process, four steps between a relay and the MA introduce communication delays: (1) A query is sent from a zone 3 protection relay r to the MA, when it sees a temporary issue (e.g., a voltage surge); (2) Once the MA receives the query from r, the MA checks with other related relays $\{r'$: $r' \in R_l$ and $r' \neq r\}$; (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. To avoid a false trip at r, the total delay for the above four steps cannot exceed the delay requirement configured at r. We ensure the transmission delay via link capacity reservation, as presented in the following.

We first determine the delay requirement from a relay to the MA based on the following procedure. For $l \in L_b$, we find two relays r_1 and r_2 from R_l, who have the *largest* and the *second-largest hop count* h_{r_1} and h_{r_2} to the MA, respectively. (When network links have different capacities, we can then use the minimum path delay for this step.) The delay requirement of zone 3 protection of each relay is initialized to a default value D_0. (For ease of illustration, we assume that all zone 3 relays have the same requirement. However, the requirement of each relay could be different constants, and we can represent them as $D_0(r_i)$ for relay r_i.) To ensure the delay requirement in the zone 3 protection procedure, we proportionally divide the total delay requirement between these two relays: in case that one is a zone 3 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 $d_1 = \dfrac{h_{r_1} \cdot D_0}{2(h_{r_1} + h_{r_2})}$; the delay requirement between r_2 and the MA is set to $d_2 = \dfrac{h_{r_2} \cdot D_0}{2(h_{r_1} + h_{r_2})}$. For other relays of l, their round trip delay requirements are set as not larger than d_2, because their path lengths to the MA are equal to 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 zone 3 protection.) The delay assignment algorithm is given in Algorithm 1.

Reservations at each hop. The existing agent-based solution assume that a dedicated path is given between a relay and the MA in order to guarantee the delays of their message exchanges using TCP. Once we have the delay assignment for each relay, we can then reserve corresponding bandwidth on the path from the relay to the MA. As the path has h_r hops from a relay r to the MA, we equally divide the path delay requirement d_r at each hop as per hop delay requirement d_r/h_r, as in many existing methods. (We will further discuss other advanced assignment methods in the next section based

Algorithm 1 Delay Requirement Assignment Algorithm for Zone 3 Protection Relays.

Input: Transmission line set L of a power network; Delay requirements for zone 3 relays
Output: Delay assignment D for zone 3 relays
Method:

for each relay r in the system **do**
  $d_r = \infty$ ▷ Initialize all delay assignments of relays
end for
for each line $l \in L$ **do**
  Find relay r_1 and relay r_2 in R_l ▷ Find two relays furthest from the MA with hop counts h_{r_1} and h_{r_2}
  determine d_1 for r_1 and d_2 for r_2
  if $d_{r_1} > d_1$ **then** ▷ d_{r_1} is the current assignment for r_1
    $d_{r_1} = d_1$ ▷ Assign a new delay requirement to r_1
  end if
  if $d_{r_2} > d_2$ **then** ▷ d_{r_2} is the current assignment for r_2
    $d_{r_2} = d_2$ ▷ Assign a new delay requirement to r_2
  end if
  for each relay $r \in L_l$ and $r \neq r_1$ and $r \neq r_2$ **do**
    if $d_r > d_2$ **then** ▷ d_r is the current assignment
      $d_r = d_2$ ▷ Assign d_2 to r
    end if
  end for
end for

on more concrete system requirements for comparison.) For ease of illustration, we assume all the request and response packets have the same size of L_0. Then, the capacity to be reserved at each communication link l on the path j from r to the MA is $C_{\text{rsv}}(l, j) = \dfrac{L_0 \cdot h_r}{d_r}$, where d_r is the delay assignment of relay r obtained based on Algorithm 1. When we consider that k paths from different relays share a link, the total reservation on a communication link l is denoted as $C_{\text{rsv}}(l)^{\text{Total}} = \sum_{j=1}^{k} C_{\text{rsv}}(l, j)$, where $C_{\text{rsv}}(l, j)$ is the reservation for r whose path j contains link l, and k is the total number of paths containing l. We present the bandwidth reservation algorithm in Algorithm 2. Note that this requirement is for a *single* protection application.

Algorithm 2 Bandwidth Reservation Algorithm for Zone 3 Protection Relays.

Input: Relay zone 3 delay assignment D.
Output: Bandwidth reservations on link set L.
Method:

for each network link $l \in L$ **do**
  $b_{\text{rsv}}(l) = 0$;
  for each path from r to the MA containing link l **do**
    $b_{\text{rsv}}(l) = b_{\text{rsv}}(l) + C_{\text{rsv}}(l, r)$;
  end for
end for

Now use the IEEE 39-bus system (as shown in Fig. 2) to illustrate the reservation process. It has 34 transmission lines and 68 protection relays. We assign the MA at bus 16 because the maximum hop count from bus 16 to other nodes is the minimum, compared with all other nodes, and it also has the highest connection degree in the system. (How to select the MA location is another interesting problem, which is out of the scope of this paper.) Each bus is within a substation that may contain several relays, e.g., bus 16 is connected with five transmission lines, thus there are 5 protection relays in this substation. We assume the communication links between each substation are the same as the power connection and each link has the identical capacity as in the previous projects. To fulfill the strict latency requirement, each of the applications should be assigned enough capacity. Assume all applications have identical packet size of 80 bytes, e.g., a basic PMU packet. Applying Algorithm 2, we observe that: for zone-3 protection, the highest reservation is 293 Kbps at link between bus 15 and bus 16. However, this is only for the zone 3 protection on this network. (Many other applications need to share the network resources.)

Scalability: Limitations of the basic reservation scheme. As we mentioned, with the development of SG, more control and monitoring applications

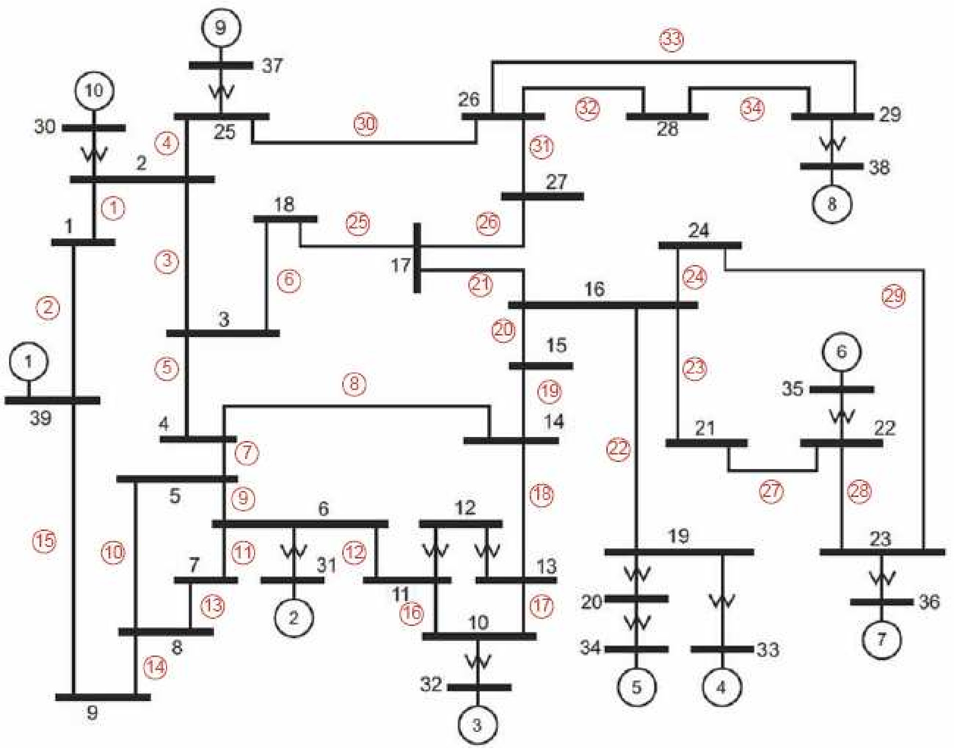


Fig. 2 IEEE 39-bus system[9].

will be deployed, such as the zone-3 protection or Phasor Measurement Unit (PMU) applications. When we have to support many real-time applications, the reservation with the above scheme will quickly grow in proportional to the number of applications. Given a network with fixed network link capacity, we can find out how many applications can be supported on the network. As we know, there are many potential applications that have the similar or higher level of traffic requirements as zone 3 protection. Zone 3 protection is just one of many control and protection schemes.

When using the static method presented in the above, the number of applications that can be assigned on a link l is determined as $\mathrm{MIN}\left\{\dfrac{C_l}{\sum C_{\mathrm{rsv}}(l)}\right\}$, where C_l is the total capacity of link l. For the 39-bus system, assume the corresponding communication link capacity is 5T1 ($1.54\,\mathrm{Mbps} \times 5$), for all links[20]. On such a system, if consider all applications to be the same priority such as zone 3 protection, with similar reservation requirements, we can then support at most 26 such applications on this system; for many other applications (such as PMU applications) that usually have high bandwidth requirements, only a few real-time applications can be supported on this network. Furthermore, the above scheme assumes normal network conditions. When more complex network applications are considered, the scalability quickly becomes an issue in supporting more real-time applications. Therefore, we must develop more efficient schemes, and we focus this issue in the following investigation.

3.1.2 Smart reservation scheme

To further improve network efficiency, let us consider more specific conditions in practical systems. In general, we usually see very few relay errors simultaneously. In most cases, we often have a single failure in the system. As a result, only one protection area is involved in communications with the MA. So, we do not have to reserve bandwidth for all relays at the same time as in the above basic scheme, in which we reserve bandwidth for each relay at every link on its path to the MA. In such a single failure case, when multiple relay-to-MA paths are overlapping on a link, we only need to reserve the maximum bandwidth requirement for them. We use Algorithm 3 to perform smart bandwidth reservation under this single failure case.

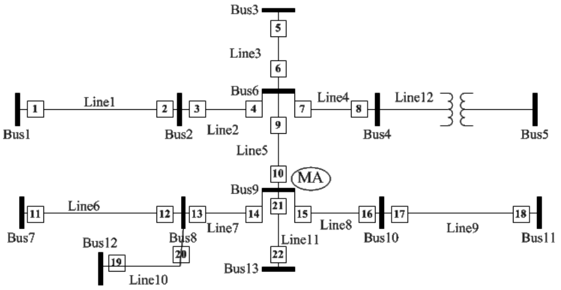
Algorithm 3 Bandwidth Reservation Algorithm for Zone 3 Protection Relays for a Single Failure.

Input: Relay zone 3 delay assignment D, bus set L_{b} and communication link set L_{c}.
Output: Bandwidth reservations on links L_{c}.
Method:

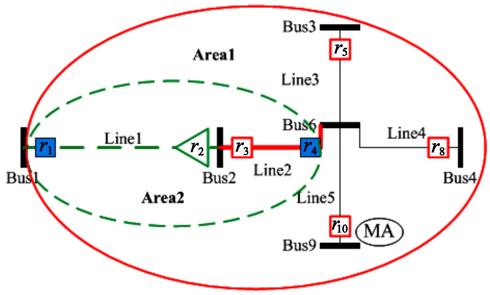
```
For each communication link l ∈ L_c, initialize b_rsv(l) to 0
for each power line l_p ∈ L_b do
    For all l ∈ L_c, set C_rsv(l) to 0  ▷ C_rsv(l) is the calculated reservation
    Find relay set R_s for l_p, which contains primary relay set R_p and backup relay set R_b
    for each relay r_i ∈ R_s do
        Calculate the reservation C_rsv(r_i, l) for all communication links l in path (r_i, MA)
        C_rsv(l) = C_rsv(l) + C_rsv(r_i, l)
    end for
    for each l ∈ (r_i, MA) do
        if C_rsv(l) > b_rsv(l) then
            b_rsv(l) = C_rsv(l)   ▷ Reserve for the maximum possible capacity usage
        end if
    end for
end for
```

As the above scheme, all relay-to-MA paths form a spanning tree rooted at the MA. While each relay may fail with a probability, only one failure occurs at a time. Given the system topology, for each power transmission line l_{p}, we can identify its protection area that includes a set of relays R_{s} that are responsible for the protection. We divide these relays into two sets: primary relay set R_{p} and backup relay set R_{b}. In general, a relay knows which line it is monitoring. Then for a transmission line, the abnormal reading at a backup relay would result in a fixed set of relays R_{s} communicating with the MA. (As primary relays will take actions almost immediately when abnormal readings are detected, in general they do not need to consult the MA for making a decision.) Notice that usually a communication link l is shared by different subtrees that the reservation on the link should fulfill the requirement of all subtrees. However, due to the high requirement of the reliability of power system, a single failure at a relay is the most common error so that not all relays in the subtrees have data to send.

For example, Fig. 3a shows the IEEE 13-bus system, and Fig. 3b shows two protection areas for the system. Area 1 and Area 2 are partially overlapped protection areas for power transmission lines Line1 and Line2, respectively. The two target transmission lines are



(a) IEEE 13-bus system



(b) Protection areas

Fig. 3 Smart reservation on a system. Under the single failure condition, only a few relays will generate traffic at a time. The system can be divided into different protection areas with the corresponding sets of relays.

marked as the red bold line between r_3 and r_4 and the green dotted line between r_1 and r_2. Here we have seven relays: four relays only belong to Area 1 (red rectangles r_3, r_5, r_8, and r_{10}); one relay only belongs to Area 2 (the green triangle r_2); and two relays are used in both areas (blue solid rectangles r_1 and r_4). Assume for relay r_i, the required capacity on a link l is $b_{\text{rsv},i}(l)$. On communication link Line5, Area 1 needs a bandwidth reservation of $\sum\limits_{i=1,3,4,5,8,10} b_{\text{rsv},i}$, while Area 2 needs a bandwidth reservation of $\sum\limits_{i=1,2,4} b_{\text{rsv},i}$. Under the condition of single relay failure, only one area would communicate with the MA across communication link Line5, although this link is on the paths for all seven relays to the MA. When any of zone-3 relays $\{r_1, r_5, r_8, r_{10}\}$ sends a request to the MA, traffic will be generated for protection Area 1. For protection Area 2, r_4 is the only zone 3 relay. It may send a request to the MA due to abnormal readings on Line1. It is obvious that reserving the larger requirement of these two areas on the link will achieve the protection of both areas. We will compare the performance and effectiveness of this scheme with the basic scheme in the next section.

3.2 Better reliability with backup paths

In real-world deployment, the system faces various issues due to the unreliability of communication networks, such as link failures, natural disasters, or configuration errors. When power devices have problems, the co-located communication network usually also experiences difficulties. Although these failures maybe seldom occur but cannot be completely eliminated. The ideal network conditions (assumed in the previous methods for transmitting queries and responses) are compromised in such situations. The delay guarantee for such messages may be violated because the communication paths may not always be available. To support these critical data exchange, we propose to use *backup paths* to address this issue in order to further improve the effectiveness of agent-based zone 3 protection.

Algorithm 4 shows how we conduct backup paths for primary paths. First, for each relay has a backup path, we need to ensure the communication network can support this. Because we assume the communication network has the similar topology as the power network, a bus may only have a single path to the MA. Thus, for these buses, we need to add a few more communication links to form a second path for the relay, which is different from its primary path. After finding a shortest backup path, we design different methods to divide the delay requirement from a relay to the MA along that backup path. The first method is to equally divide the delay requirement at each hop, as in the basic delay assignment for primary paths. The second method considers the hop distance from a relay to the MA on a path. The motivation is that communication links closer to the MA usually are shared by more paths than those further away from the MA. The third method considers the loads of different links on a path. Another method is to consider both hop distance and link load in the delay assignment.

To apply the above delay assignment methods, we design different delay assignment weights for a relay at each hop of its path to the MA, as shown in Weight Function 1 (based on hop distance), Weight Function 2 (based on link load), and Weight Function 3 (combination of hop distance and link load). The hop distance based scheme is shown in Weight Function 1. For a relay r, the weight at hop i on the backup path p is calculated as $w_i = \dfrac{\sum\limits_{i\in p} h_{\text{bp}}(i)}{h_{\text{bp}}(i)}$, where $h_{\text{bp}}(i)$

Algorithm 4 Backup-Path Algorithm for Zone 3 Protection Relays.

Input: All communication links L_c and network topology.
Output: Backup path set P_b with bandwidth reservation
Method:

```
for each link l ∈ L_c do   ▷ Single link failure can be handled
    Identify primary path set P_a affected by the failure of l
    for each p ∈ P_a do
        Find a shortest backup path for p (The backup path may consist of two parts: the part not overlap with p and the one overlap with p)
        For relay r associated with path p, decide how to divide delay requirement D_0 at each hop i on its backup path p_bp(r), using one of four alternative schemes: equal assignment, Weight-Function 1, Weight-Function 2, or Weight-Function 3, to set up weight w for all links on p_bp(r)
        for each hop i along the backup path p_bp(r) do
            l_i is the forward link from hop i to the MA
            Set delay requirement at i using link weight w_i as D_r(i) = D_0 · w_i / Σ_{i∈p} w_i
            Reserve bandwidth at l_i is B_rsv(i) = L / D_r(i)
            if l_i is not overlapped with the primary path of r then
                Set reservation C_rsv(i) = B_rsv(i)
            else
                Identify the reservation C_rsv,pr on the primary path
                set reservation for r as C_rsv(i) = max{B_rsv(i), C_rsv,pr(i)}   ▷ Primary path and Backup path would not be used at the same time
            end if
        end for
    end for
end for
```

is the hop count from hop i to the MA. Then, each hop i is assigned a local delay requirement of $D_r(i) = D_0 \cdot \frac{w_i}{\sum_{i \in p} w_i}$, where D_0 is the one-way delay requirement already calculated for relay r at the primary path assignment. For example, for three hops with hop distances 3, 2, and 1, their weights are 2, 3, and 6, respectively; their per-hop delay assignments are $\frac{2}{11} D_0$, $\frac{3}{11} D_0$, and $\frac{6}{11} D_0$. The closer to the MA, the larger local delay requirement will be, resulting in a smaller bandwidth reservation.

The link load based scheme is shown in Weight Function 2. We calculate the weight as follows. Assume for a relay r, we already find a shortest backup path p.

Weight Function 1 for per-hop delay assignment

Input: Backup path p_b of relay r.
Output: Delay assignment of each hop on p_b
Method:

```
Identify the relays delay requirement of path p_b
for each hop i along the backup path p_b do
    Identify the hop count h_bp(i)
end for
for each hop i along the backup path p_b do
    Set weight w_i = Σ_{i∈p} h_bp(i) / h_bp(i)
end for
```

Weight Function 2 for per-hop delay assignment

Input: Backup path p_b of relay r.
Output: Delay requirement of each hop on p_b
Method:

```
Identify the relays delay requirement of path p_b
for each hop i along the backup path p_b do
    l_i is the forward link from hop i to the MA
    Identify the current reserved capacity C_rsv(l_i) and link capacity C(l_i)
    Set a(l_i) = 1 − C_rsv(l_i) / C(l_i)
end for
for each hop i along the backup path p_b do
    Set weight w_i = Σ_i a(l_i) / a(l_i)
end for
```

Weight Function 3 for per-hop delay assignment

Input: Backup path p_b of relay r.
Output: Delay requirement of each hop on p_b
Method:

```
Identify the relays delay requirement of path p_b
for each hop i along the backup path p_b do
    Calculate the distance weight w_i,dst and load weight w_i,load as in Weight-Function 1 and Weight-Function 2
end for
for each hop i along the backup path p_b do
    Set the new weight at i as w_i = w_i,dst · w_i,load
end for
```

We first compute the proportion of available capacity on link $l_i \in p$ as $a(l_i) = 1 - \frac{C_{\text{rsv}}(l_i)}{C(l_i)}$, where $C_{\text{rsv}}(l_i)$ is the reserved capacity on link l_i and $C(l_i)$ is the total capacity. Here link l_i is the forward link from hop i to MA. Then, the weight at each hop i for a relay r is $w_i = \frac{\sum_i a(l_i)}{a(l_i)}$. Similarly, each hop i is assigned a local delay requirement of $D_r(i) = D_0 \cdot \frac{w_i}{\sum_{i \in p} w_i}$. We then reserve bandwidth at each hop based on such delay assignments.

The combine scheme is shown in Weight Function 3. We first follow the above steps to get the weights based on hop distance and link load, denoted as $w_{i,\text{dst}}$ and $w_{i,\text{load}}$. We then calculate the combined weight at hop i as $w_i = w_{i,\text{dst}} \cdot w_{i,\text{load}}$. As in the previous two methods, the delay requirement at hop i can be calculated using $D_r(i) = D_0 \cdot \frac{w_i}{\sum_{i \in p} w_i}$ and the link utilization is also modified.

Assume we have only one communication link failure at a time, which could randomly occur at any link. We like to find out how to minimize the impact of such single failure with backup paths.

The bandwidth reservation on a backup path is similar to that of a primary path. For example, a backup path $p_{\text{bp}}(j)$ for relay r_j at a bus is used when a link l on its primary path fails. The reservation on each link of the backup path is $C_{\text{rsv}}(i) = \frac{L}{D_r(i)}$, where L is the size of packets generated from the relay r_j, and $D_r(i)$ is the local delay requirement at hop i that we calculated with the above delay assignment methods. Note that when combining the reservation for a backup path with the reservation for a primary path on a link, we should consider the requirement of both paths. Assume path p_1 and path p_2 are primary paths for adjacent relays with reservation $C_{\text{rsv}}(1)$ and $C_{\text{rsv}}(2)$ on a link. When consider path p_1 fails, we use a portion of path p_2 as a backup path to deliver that traffic which is supposed to be transmitted over p_1. To ensure both path p_2 and the backup path of p_1 work, we should reserve at least $C_{\text{rsv}}(1) + C_{\text{rsv}}(2)$ bandwidth on each shared link on p_2. It is obvious that such a scheme requires more bandwidth and will affect the total number applications that can be supported on the system.

4 Performance Evaluation

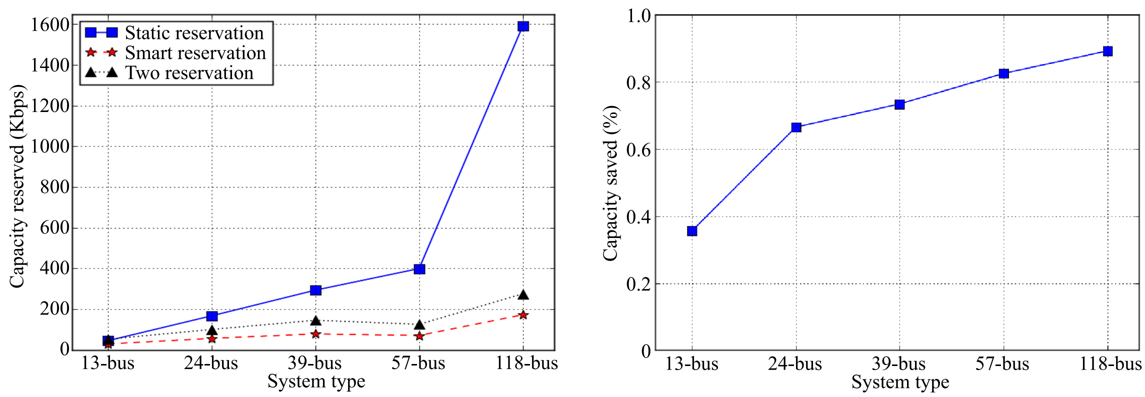
In this section, we evaluate the proposed schemes and discuss related issues for further improvement.

4.1 Comparison of the basic and smart schemes

We present the numerical result to demonstrate the advantage of the smart reservation scheme, compared with the basic scheme. As shown in Fig. 4a, we considered five different power systems, ranging from 13-bus, 24-bus, 39-bus, 57-bus, to 118-bus. The top curve shows the maximum bandwidth reservation required for the basic scheme. The bottom curve shows the maximum bandwidth reservation of the proposed smart scheme. (The middle curve is for the double hidden failure case, as explained in Section 4.2.) Clearly, the larger the power network, the more link bandwidth the smart scheme can save, compared with the basic scheme. Furthermore, Fig. 4b shows the percentage of bandwidth saved by the smart scheme compared with the basic scheme, ranging from 37% to almost 90%.

4.2 Dealing with simultaneous hidden failures

Using the master agent in the power system helps us prevent false relay trips due to hidden failures. When a power device has hidden failures, it does not mean that it is totally damaged; instead, only some of its normal functionalities are out of order. Due



(a) Bandwidth requirement

(b) Improvement of smart scheme

Fig. 4 Comparison of static and smart reservations on five power systems.

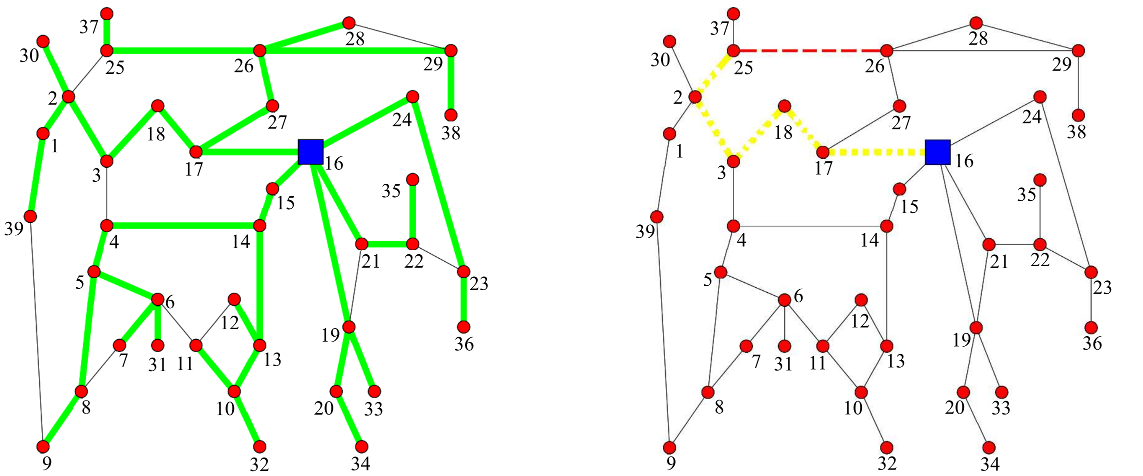
to the high reliability requirement of power systems, a device is built to work for a long period of time without maintenance. For example, its Mean Time To Failure (MTTF) should be higher than 100 000 hours[21] while its Mean Time To Repair (MTTR) is about 1 hour[22]. This yields a rather low device failure probability of 10^{-5}. However, the probability for hidden failures is much higher, e.g., the hidden failure probability of a line is given as 10^{-2}[14]. Consider that hidden failures are mostly triggered by zone 3 relays[3, 6], the Hidden Failure (HF) probability of a line can be represented as

$$P(\text{HF of a line}) = 1 - P(\text{a relay is normal})^k.$$

Assume we have k zone-3 relays for this line. We analyzed the five power systems (IEEE 13-bus to 118-bus systems), and found that the average number of zone-3 relay per transmission line is between 3.1 to 5.6. Plugging into the above formulas, we have the hidden failure probability at the level of 10^{-3} per line. We can see that the case of three simultaneous relay hidden failures is rare (about 10^{-9}). So, we do not have to consider three or more simultaneous hidden failures. As current power grid reliability requirement ranges from "three nines" (99.9%) to "five nines" (99.999%)[23], we still have to investigate the cases where two hidden failures simultaneously happen in the system. To address this issue, we extend the smart reservation scheme to deal with two simultaneous failures. Instead of reserving bandwidth for the maximum requirement on a link for multiple overlapped relay-to-MA paths, we reserve bandwidth for top-two requirements among these paths. We show the results of this scheme as the middle curve in Fig. 4a. The maximum reserved capacity on a link is a little higher than the single-hidden-failure case.

4.3 Effectiveness of backup scheme

We use the IEEE 39-bus system (Fig. 2) to demonstrate the backup scheme. The 39-bus system has 34 transmission lines and all buses connected by these lines have at least two paths to the MA, except bus 19. As we assume the communication links follow the pattern of power lines, we can find backup paths on this network for most relays. For bus 19, we add a communication link between bus 19 and bus 21 for the reliability purpose. Assume bus 21 is the closest bus for bus 19. All links have an identical capacity of 1.5 Mbps. Assume that the failure probability of a communication link is about 10^{-5}[24], which is rather close to the system failure requirement. Thus, the main consideration of backup paths here is to handle a single link failure. We use the basic scheme to find both the primary path and the backup path, since now all power buses have at least two communication paths to the MA and the system is able to handle a single link failure. (As bus 12, bus 20, and bus 30 to bus 38 either connect to generators or have no transmission lines connected, we do not need to find backup paths for them). Figure 5a shows that the primary paths from relays to the MA (bus 16) with thick green lines. Figure 5b demonstrates the backup path as a yellow dash line to deal with the failure



(a) Primary path from bus 25 to the MA

(b) Backup path for link (25, 26) failure from bus 25 to the MA

Fig. 5 Primary path and backup path. In the normal case, the path from bus 25 to the MA is (25, 26, 27, 17, 16); when the link between bus 25 and bus 26 fails, the backup path (25, 2, 3, 18, 17, 16) is used. The paths to the MA in both figures are highlighted in bold lines, and the failed path is marked as the red dash line.

of link (25, 26) on a primary path.

We can further improve the above backup scheme with the smart reservation scheme, as we usually only see single link failure. To deal with such single failure, within a set of power lines, we find out the one that requires the largest capacity on a specified link and makes corresponding bandwidth reservation. Notice that since a backup path may be longer than a primary path, the per-hop reservation for a backup path may also be larger. We evaluate such a scheme on the IEEE 39-bus system, and summarize the results of maximum link reservation in Table 1. For the cases in the first row, we add up the reservations of all relays on a link; for the second row, we reserve link bandwidth under the assumption of single hidden failure. The four columns are corresponding to the four delay weight assignment methods discussed in the above. We can see that, in general, the smart backup scheme requires much less capacity than the basic backup scheme. In the basic backup scheme, the hop distance and link load both help reduce bandwidth by lowering the maximum bandwidth reservation on links. For the smart scheme, the equal division and the load-based delay assignment outperform the other two.

4.4 Discussions

4.4.1 Potential hot spots in primary paths

A potential problem when equally dividing the delay requirement on a primary path is that it might generate hot spots around the master agent. On one side, this may be inevitable on a given network topology, since we only have limited number of path choices for relays; on the other side, we can mitigate this problem by "pushing" the capacity requirement away from the MA. A simple scheme is to divide the delay at each hop according to the hop count to the MA. We performed a test on the IEEE 39-bus system, which shows that this method can reduce the reservation at link 20 (from bus 15 to bus 16) from 293 Kbps to 150 Kbps and the reservation at link 21 (from bus 17 to bus 16) from 247 Kbps to 140 Kbps. In this way, the links closest to MA now are able to handle more application traffic.

Table 1 Comparison of maximum link reservation for basic and smart backup schemes. (Kbps)

	Equal division	Hop distance	Load	Combination
Basic	835	790	741	729
Smart	85	153	76	149

4.4.2 Responses to the MA from multiple relays

For the protection of a power line, multiple relays are involved. The MA need to query all of them whenever a relay inquires the MA because the relay sees an abnormal reading. For example, power line 8 has two primary relays (relay 15 and relay 16) and four zone 3 relays (relay 9 at bus 3, relay 14 at bus 5, relay 35 at bus 13, and relay 38 at bus 15). When one of the four zone-3 relays sees an abnormal value, it inquires the MA; other relays will be queried by the MA to make decision. If we do not consider potential network issues, each relay response is received by the MA on time, and only a few responses (one or two) are sufficient for the MA to make a correct decision. However, as we do not know which relay will inquire the MA and which response will be received first ahead of time, we need to provide resource reservation for all participating relays. This is an interesting issue to be examined in our future research.

4.4.3 Importance of transmission links and power lines

In this paper, we assume all transmission links and power lines are of the same importance. However, in practical deployment this may not be the case. Power lines may be distinguished according to their functionality, such as whether it is close to a generator or how much power it delivers. For example, in IEEE 39-bus system, under the initial setting, line 9, line 22, and line 27 carry more than 450 MW power, which is relatively higher than other lines; thus, they deserve better protection. In addition, the consequence of line failure can also be used for prioritizing the power lines. Voltage Stability Index (VSI)[25] is one good indicator for the stability condition of a power line. For example, when the reactive load at bus 28 is higher than 760 MVar, tripping power line 33 will result in the highest VSI in the system, which means the system is becoming unstable and prone to system failure; while tripping line 9 brings less changes to the VSIs of other lines. In other words, line 33 is more important than line 9 in this case. We are currently investigating the VSI-based priority of power lines for the zone 3 protection.

Another issue is the transmission link quality. Due to the fact that links at different locations in the system carry different volumes of traffic and the importance of the traffic depends on the applications. A reasonable assumption is that the reliability of links also varies accordingly. For example, links close to the MA may have a higher reliability or even equipped with a local backup link because they are critical for many applications. This point also deserves further exploration, depending on the reliability data of practical networks.

4.4.4 Overlaps of primary and backup paths

Under the condition of single communication link failure, if a backup path of a relay does not overlap with its primary path, the communication between the relay and MA is guaranteed. However, for a given network topology, a completely non-overlap backup path for each relay is not always available, which is one of the real constraints in network deployment. When a backup path is overlapping with its primary path, it will also fail if one of the overlapped links fails. When a relay sees an abnormal reading of a remote power line, it inquires the MA for a decision. If the overlapped links fail, the query or the final decision cannot be received on time so that the relay may falsely be tripped. Given the network topology and transmission link parameters, we can determine the probability for the false tripping of a power line due to communication link failure as:

$$P_{\mathrm{f}}(\mathrm{line}_i) = \sum_{\mathrm{link}_j^{i,1} \in (\mathrm{PR}_{i,1} \cap \mathrm{BP}_{i,1})} P_{\mathrm{f}}(\mathrm{link}_j^{i,1}) + \sum_{\mathrm{link}_j^{i,2} \in (\mathrm{PR}_{i,2} \cap \mathrm{BP}_{i,2})} P_{\mathrm{f}}(\mathrm{link}_j^{i,2}),$$

where $r_{i,1}$ and $r_{i,2}$ are the two relays that locate at each end of line$_i$; $\mathrm{PR}_{i,1}$, $\mathrm{PR}_{i,2}$, $\mathrm{BP}_{i,1}$, and $\mathrm{BP}_{i,2}$ are the primary and backup paths for the relays, respectively; $\mathrm{link}_j^{i,1}$ and $\mathrm{link}_j^{i,2}$ are the j-th link of the backup paths for the two relays, and each of them is on the overlapping portion of the primary and backup paths of a relay.

As an example, we examine the case when using a shortest path as a backup path for the primary path. The overlapping condition of primary and backup paths is shown in Fig. 6, in which the overlapping ratio is calculated as the ratio of the number of overlapping link on a backup path to the number of total hop count of the backup path. We assume each communication link has a failure probability of 10^{-5}. The false tripping probability of each power line due to a communication link failure is shown in Fig. 7. As we usually expect the failure probability of a power line does not exceed a given threshold, the backup scheme works when the threshold is 10^{-4} as the horizontal dash line shown in the figure: All lines meet the requirement. However, as the requirements vary for different applications and some may require much higher reliability, the backup path also needs improvement to fulfill more strict requirements.

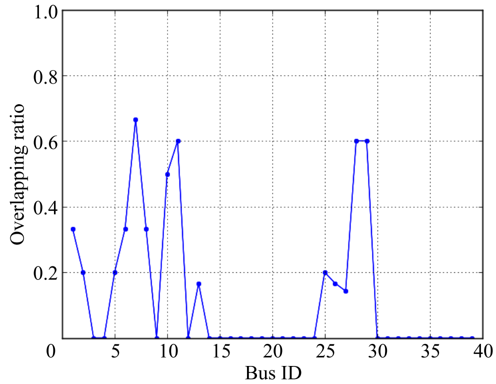


Fig. 6 Overlapping condition of primary and backup paths in 39-bus system.

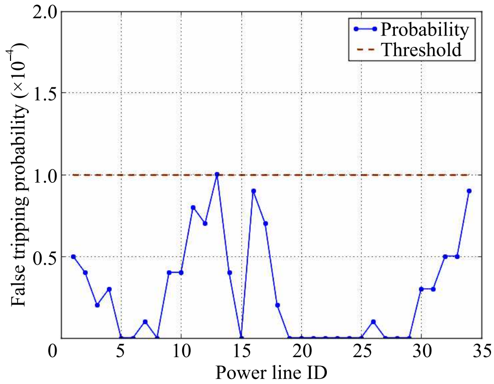


Fig. 7 False tripping probability in 39-bus system.

5 Conclusions and Ongoing Work

In this paper we have examined the existing agent-based solutions and proposed several new methods to further minimize the false trips of zone 3 relays. Our analysis and simulation results show that the proposed schemes can further reduce the potential zone 3 relay errors and improve the stability of power systems.

Although the above proposed scheme may work well for a limited number of applications, the scalability of such schemes may become an issue as more and more SG applications are being deployed[12, 16, 17]. We are currently further investigating a statistical network management scheme to address the scalability issue. Such a scheme can support many important real-time applications with a low chance of control failures.

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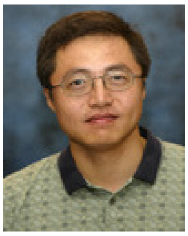

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