THE SHANGHAI PRACTICE: IMPROVE THE RELIABILITY OF URBAN MV DISTRIBUTION SYSTEM WITH K-STATION AND ITS NEW NETWORK DESIGNS

Ruochen SONG
State Grid Shanghai Municipal
Electric Power Company – China
song_yanshu@hotmail.com

Jingjing LU
State Grid Shanghai Municipal
Electric Power Company – China
looloo1755@163.com

Mingze ZHANG
State Grid Shanghai Municipal
Electric Power Company – China
casey.zhang1985@hotmail.com

ABSTRACT

In downtown Shanghai, there are more than 1500 K-stations that compose the backbone of MV (middle voltage) distribution system. As the power service availability in the city center hit the milestone of 99.99% in 2017, electrical researchers and grid managers are targeting higher goals such as fast recovery from n-1-1 contingencies in MV system. Three new network architectures of K-stations are proposed in order to achieve higher reliability. To examine the effects of these proposals, this paper introduces an analysis model simulating urban distribution networks, an innovated reliability evaluation approach that puts special efforts on differentiating performances in response to multiple contingencies, and also a cost-effectiveness analysis approach. With these tools, each proposal's advantage in reliability and its disadvantage in cost compared to the traditional design have been analyzed, quantified and compared. Based on this research, power grid managers have found a feasible solution to keep on improving their services to electricity customers in Shanghai.

INTRODUCTION

K-station, called by grid managers in Shanghai who are faced with tremendously high load density and extremely limited public spaces, refers to MV switching station with Shanghai characteristics. A K-station is normally arranged as a single busbar system divided into two sections. Each section are equipped with circuit breakers connecting to one incoming supply cable, which is sized to support both sections, and 3 to 6 outgoing feeders. When K-station was firstly introduced two decades ago, it served as the subsidiary of a HV/MV substation with the fundamental goal to expand the substation's busbar. But its ability to withstand the loss of one power source soon became a driving force of system reliability growth. Moreover, by smart deployment of K-stations, the substations could be downsized. Thanks to these benefits, K-stations have now composed the backbone of MV network in Shanghai. There are more than 1500 K-stations in the city center alone, in contrast to around 200 substations.

In 2017, the power service availability in the city center hit the milestone of 99.99%, largely because all major distribution components had satisfied n-1 criteria which requires all loads restored quickly if any single component fails. Now, in order to achieve even higher reliability, grid managers are considering the feasibility and cost-effectiveness of reinforcing K-stations to satisfy n-1-1 criteria. Though the concept of n-1-1 criteria is common in the research field of transmission system [1], it has been rarely considered for distribution system [2][3][4] because of the seemingly low probability of cascading contingencies. However, in cities like Shanghai where infrastructure investments still drive the local economic growth, constructions or reconstructions of roads, tunnels, subways and other infrastructures often lead to planned outages of distribution components lasting for months. In this scenario, a following n-1-1 contingency is actually inevitable over time.

To satisfy n-1-1 criteria, K-stations should accord to more complicated network architectures. This paper firstly proposes three such designs. The MV distribution system is then simplified as a symmetric model, based on which the system's reliability can be evaluated with analytic approaches. In opposite to traditional analytic approaches [2][3][4], an approach named Recursive Tree Algorithm is introduced to take cascading contingencies into account. Complemented by annul cost evaluation and cost-effectiveness analysis, this paper delivers a full picture of pros and cons of the three proposals.

I. NEW DESIGNS OF K-STATION NETWORK

A. Network architectures

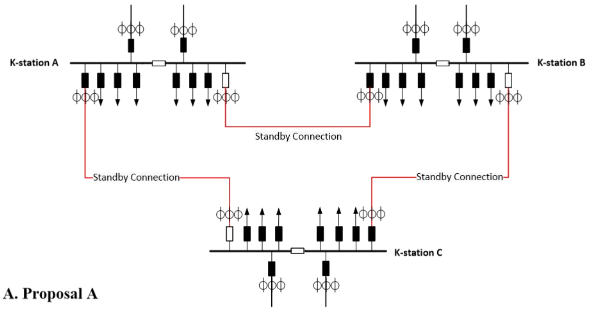
In order to restore all loads quickly after n-1-1 contingencies, K-stations need more directions to transfer their loads. Based on this principal, there are three proposals of reinforced network designs as **Figure 1** shows.

1) Proposal A: Each K-station is supplied directly by a substation. Each busbar section reserves one branch as a standby connection with a neighboring K-station. In the normal state, this connection has one end closed and the other open. When necessary, it can be activated to transmit power to either side by a single operation.

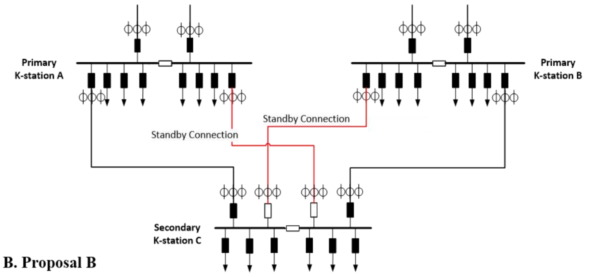
2) Proposal B: A K-station's group is composed of 2 primary K-stations that are directly supplied by substations and a number of secondary K-stations whose power is relayed by other K-stations. In the whole group, only 2 connections are normally in standby mode.

3) Proposal C: It appears similar to Proposal A. But here the direct standby connections are replaced with indirect connections. Two feeders from adjacent K-stations are

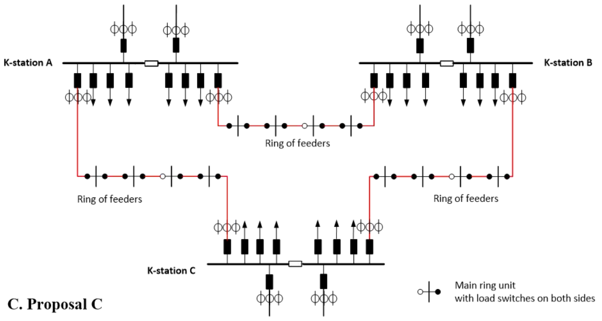
connected at the ends, therefore composing a ring. Typically, the ring is operated in an "open-ring" arrangement, but its cable is sized to bear extra loads of a busbar section. So closing the ring will form an indirect connection between K-stations.



A. Proposal A



B. Proposal B



C. Proposal C

Figure 1. Circuit configurations of a network composed of 3 K-stations in accordance to the proposed designs

Other than the existing sectionalizing breaker, now each busbar section have an additional standby connection. This additional connection provides load transfer capacity between K-stations and indirectly between substations. Not only is a K-station's dependence on its master substation reduced, but also it has more backup routes to obtain power when outages occur. However, due to more investments on cables, breakers and protections, the system's cost-effectiveness is expected to decline.

B. Operation modes

Base case

In Proposal A and C, a K-station is directly supplied by its nearest substation, same as by tradition. In Proposal B, a primary K-station is supplied by its nearest substation, whereas a secondary K-station is supplied by an adjacent K-station or K-stations on both sides, depending on the load balance strategy.

System adjustments after a primary contingency

If losing one power source due to an n-1 contingency, a K-station in Proposal A and C will resort to its other source in operation, simply by segregating the failed one and then closing the sectionalizing breaker. In Proposal B, the adjustments in n-1 state can be optimized to be better prepared for a secondary contingency. So after the isolation of the failed component, the associated standby connection is prioritized to be activated to restore power, in which case all sectionalizing breakers stay open.

System adjustments after a secondary contingency

Since each busbar section has a sectionalizing breaker and an additional connection as backup sources, there are multiple ways to adjust in case of an n-1-1 contingency. The only principal to follow is that adjustments shouldn't lead to current overloads. In Proposal A and C, a K-station losing both power sources will rely on its neighboring K-stations on both sides. It is recommended to transfer half its load to each neighbor, thus no more than 2 busbar sections will be supplied together so as to avoid overloads. In Proposal B, sectionalizing breakers have been recommended to stay open in n-1 state. If so, the solution to n-1-1 adjustment is as simple as closing the sectionalizing breaker. The maximum number of busbar sections being supplied together equals the number of K-stations in the group.

C. Load capacity

By tradition, a K-station is supplied through two 3×400mm^2 copper cored and XLPE insulated cables whose rated current is around 400A. In accordance to n-1 criteria, a K-station therefore should support loads of no more than 7MW.

Same capacity per station and size of supply cables are recommended for Proposal A and C. The standby connection in Proposal A should be sized for the capacity of a busbar section which equals 3.5MW. The indirect connection in Proposal C should be able to support its own loads plus another 3.5MW. Therefore, 3×185mm^2 and 3×240mm^2 copper cables are recommended for each case. In Proposal B, the capacity per station has to be balanced with the number of stations in a group to avoid any overload. If the capacity is still 7MW and the number is 3, two pairs of coupled 3×400mm^2 copper cables are recommended for supply cables of primary K-stations as regular 3×400mm^2 cables for secondary K-stations.

D. Protection and automation

To detect and isolate faults accurately and quickly, longitudinal differential protections are recommended as the primary protection for supply cables and direct connections between K-stations. Feeders should be protected by regular overcurrent and zero sequence current protections. However, when a ring of feeders is used as an indirect connection between K-stations, the lack of differential protection may cause a problem. For instance, if a fault occurs as shown in **Figure 2**, breaker

B3 is expected to isolate the fault. But breaker B1 is protected by the same strategy, so the fault current may cause it to break ahead of B3, leading to an expansion of outage. One solution is to set the overcurrent operating time of breakers such as B1 and B2 longer than others.

When a fault is successfully isolated, the network should automatically restructure following the adjustment strategies introduced before. Automation is easier to implement at K-stations where circuit breakers by default are equipped with remote terminals. Automation of feeders, however, requires to remotely control load switches, which is much harder to implement in the urban area, sometimes impracticable.

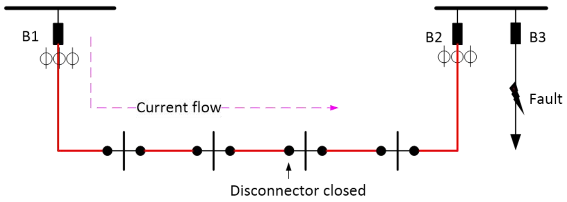
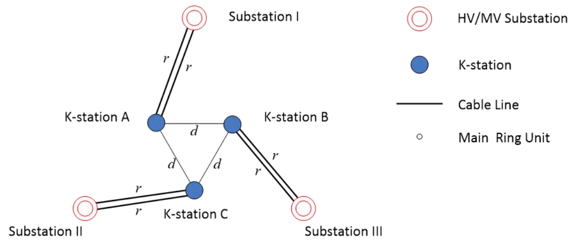
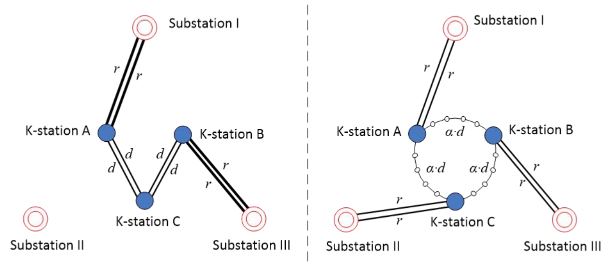


Figure 2. An occurrence of fault in Proposal C when an indirect connection between K-stations is enabled



A. **Proposal A**



B. **Proposal B**

C. **Proposal C**

Figure 3. Architectures of the analysis model

II. ANALYSIS MODEL AND ASSUMPTIONS

In this model, the electrical loads are assumed to be evenly distributed. Substations are assumed to be both equally sized and equally loaded. So are K-stations. Therefore, any two adjacent substations (or K-stations) should be equally apart with each other in a distance determined by the load density and capacity per station. Suppose that 3 K-stations compose a group. Architectures of such a group following different network designs are as **Figure 3** shows.

Here are more assumptions for the model:

1) Load density ranges from 5 to 80MW/km^2.

2) Substation's capacity is 2×40MVA, power factor 0.95, and average load factor 65%.

3) K-station's maximum load allowed is 7MW, with the average load factor of 80%.

4) Length of supply cables connecting substations with K-stations equals r that represents the average power supply range of a substation.

5) Length of direct connections between K-stations equals d that represents the direct distance between adjacent K-stations. Length of indirect connections in Proposal C equals $\alpha\cdot d$ where α stands for a detour coefficient.

6) Feeders are supplied by K-stations and connected in pairs. 50% of them can be remotely controlled while the others can only be manually operated.

7) Outages of distribution components are mutually independent events.

III. RELIABILITY ANALYSIS

A. Basic Definitions

The i-th component's annual average stoppage frequency (occurrences per year) and average duration per stoppage (hours) are denoted as $\lambda(i)$ and $t(i)$. The unavailability of the i-th component $\rho(i)$ equals [5]:

$$\rho(i)=\frac{\lambda(i)\cdot t(i)}{8760} \tag{1}$$

For a set of connected circuit components among which a fault cannot be isolated, denoted as $\boldsymbol{I}$, it could be seen as a single component with $\lambda(\boldsymbol{I})$ or $\rho(\boldsymbol{I})$ equal to the summation of $\lambda(i)$ or $t(i)$ for each i belonging to $\boldsymbol{I}$ [5].

The system is expected to supply unceasing power to each component i, but fails sometimes. Use $v(i)$ to denote the system's annual interruptions of power supply to component i, $\mu(i)$ the system's unavailable probability of power supply to i, and $\tau(i)$ the i-th component's average duration per interruption. Note their differences from $\lambda(i)$, $\rho(i)$ and $t(i)$ which are determined by component i alone.

B. Recursive Tree Algorithm

From a load's point of view, its power supply system could be seen as a tree structure. There are multiple possible routes for current to flow from the tree's leaves (HV/MV interfaces) to the root (load). To assess the system's service reliability to a load, we are evaluating the overall available probability of these routes.

HV/MV interfaces, busbar sections and loads are defined as nodes on the tree, whereas other components compose branches. Searching upstream along the routes from node n, there may be one or multiple father-nodes via different branches. The total number of father-nodes that may relay power to n is denoted as $K(n)$. Each father-node is denoted as $f_k(n)$ ($k\in\{1,2,\ldots,K(n)\}$), among which $f_1(n)$ is defined as the primary father-node where current flows from in normal state. $\boldsymbol{R}_k(n)$ represents the set of components on the branch between n and $f_k(n)$, which may also include the attached components that the branch cannot be segregated from.

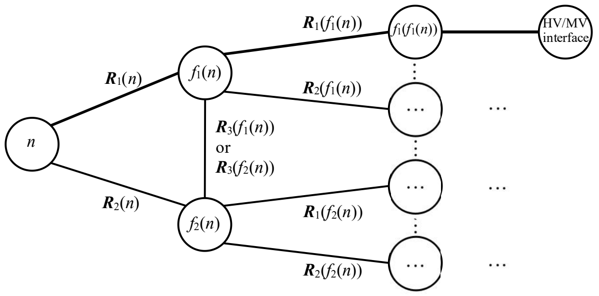


Figure 4. An example of the tree structure

Stoppage of node n itself or its primary branch $\boldsymbol{R}_1(n)$, or the interruption of its primary father-node $f_1(n)$, will lead to the power interruption of node n. Therefore:

$$\nu(n) = \lambda(n) + \lambda(\boldsymbol{R}_1(n)) + \nu(f_1(n)) \tag{2}$$

$$\mu(n) = \rho(n) + \frac{E_{\tau|\overline{\boldsymbol{R}}_1}(n)}{8760}\left[\lambda(\boldsymbol{R}_1(n)) + \nu(f_1(n))\right] \tag{3}$$

$$\tau(n) = 8760\frac{\mu(n)}{\nu(n)} \tag{4}$$

where $E_{\tau|\overline{\boldsymbol{R}}_1}(n)$ stands for the expected value of interruption duration of node n given that its power supply from the primary branch has failed. Given the unavailability of power from the primary direction, if no other branch and its associated father-node is functional, whose probability is denotes as $P(n)$, the interruption will last till the fastest recovery of any branch and its associated father-node. Otherwise, the interruption will only last for a duration needed for system adjustment, denoted as $T(n)$. Thus:

$$E_{\tau|\overline{\boldsymbol{R}}_1}(n) = P(n)\cdot\min_k \max\left[t(\boldsymbol{R}_k(n)), \tau(f_k(n))\right] + \overline{P}(n)\cdot T(n) \tag{5}$$

If these branches and their associated father-nodes are mutually independent, then:

$$P(n) = \prod_{k\neq 1}\left[\rho(\boldsymbol{R}_k(n)) + \mu(f_k(n))\right] \tag{6}$$

So the Recursive Tree Algorithm is written as following.

```
function recursive_Tree ( node n )
        if      infinite loop or current overload is detected
                return  $\nu(n)=1,\ \mu(n)=1,\ \tau(n)=8760$
        elseif  node n is HV/MV interface
                return given statistical data
        else
                search upstream and assign $K(n)$
                identify $f_k(n)$, $\boldsymbol{R}_k(n)$ for all k
                call recursive_Tree ($f_k(n)$) for all $f_k(n)$
                calculate $\nu(n)$, $\mu(n)$, $\tau(n)$ by Equation (2)-(6)
                return results of $\nu(n)$ , $\mu(n)$ , $\tau(n)$
        end
```

Run the algorithm for each load to get each one's $\nu(\ )$ and $\mu(\ )$. Since all loads are assumed to be equivalent, system reliability evaluation indexes such as SAIFI (system average interruption frequency index), ASAI (average service availability index) and SAIDI (system average interruption duration index) can be easily calculated [2][3].

Table 1. Statistical data for reliability analysis

Component	Annual outage frequency (occurrences per year)	Average outage duration (hours per incident)
HV/MV interface	0.12	38
Circuit breaker	0.17	13
Busbar section	0.03	42
Load switch	0.13	12
Cable per km	0.18	15

Both planned and unplanned outages have been taken into account.

C. Observations from Case Study

Analysis has been performed for the model introduced before, based on data from **Table 1**. Besides, the average time to remotely operate a K-station is assumed to be 3 minutes. Operating a load switches on a feeder remotely takes 5 minutes whereas manually takes 2.5 hours.

Outcomes of ASAI evaluation for each design is shown in **Figure 5**. Given the limited space available, results of SAIFI and SAIDI are not shown by figures. The analysis indicates that the reliability generally gets better as the load density grows. Compared to the traditional design, both ASAI and SAIDI are improved by the proposals. Among the three, Proposal A is the most effective one, reducing SAIDI by 3.51~2.35% as the load density varies from 5 to 80 MW/km^2. Proposal C ranks the second with 2.36~1.76% reduction of SAIDI. Proposal B reduces SAIDI the least by 1.77~0.98%. However, none of the proposals manages to reduce the annual SAIFI that originally equal to 1.33~1.03. The index is unchanged in Proposal A or C, while rises 16.9~14.4% in Proposal B.

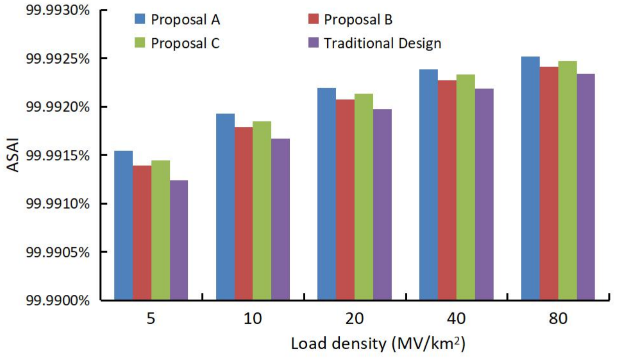


Figure 5. Results of ASAI evaluation for each design

IV. ECONOMIC ANALYSIS

A. Analysis Approach

Introduce the index named ACPL (annual cost per load) for cost evaluation. Annual cost is composed of yearly amortized investment and annual operational costs [3][5]. The former is the yearly amortization of initial investment over the system's projected life. Therefore:

$$F_m = Z_{\mathrm{S}}\frac{r_0(1+r_0)^m}{(1+r_0)^m - 1} + U_{\mathrm{S}} \tag{7}$$

where F_m represents the annual overall cost over m years, m the years of the system's projected life, Z_{S} the initial building investment of the system, r_0 the average return ratio of electrical industry. U_S represents the operational costs including repairing, maintenance and so on. Here m is chosen as 30 and r_0 as 6%.

Then the system's ACPL denoted as F equals:

$$F = \frac{F_m}{L} \tag{8}$$

where L represents the average load in total.

With results of both cost and reliability evaluation on hand, the cost-effectiveness of each proposal can be measured by SAIDI reduction divided by ACPL increase, compared to the traditional design.

B. Observations from Case Study

Here, components taken into account include K-stations, cables, feeders, ring main units, MV/LV transformers, protections and fibers. With their costs shown in **Table 2**, ACPL has been calculated for each design, the results illustrated in **Figure 6**. The cost generally gets cheaper as the load density grows. Unsurprisingly, the traditional design is always the cheapest. Compared to that, ACPL of Proposal A rises 4.98~2.51% as the load density varies from 5 to 80 MW/km². Proposal B increases ACPL by 14.29~6.79% and Proposal C by 3.86~1.66%.

Figure 7 shows the results of cost-effectiveness analysis. The cost-effectiveness of each proposal generally improves as the load density grows. Proposal A is the most cost-effective one when the load density is lower than 10MW/km². When the density is higher, the most cost-effective one is Proposal C whose gradient is as well the highest. Proposal B is the least cost-effective plan.

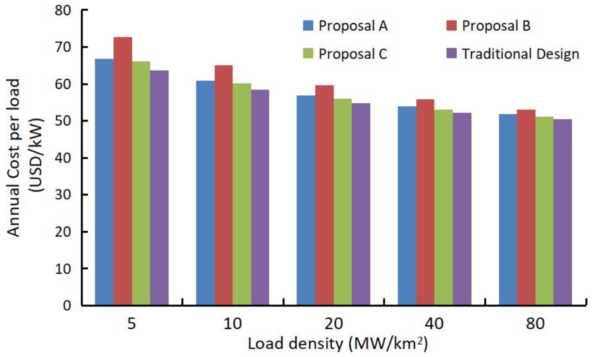


Figure 6. Results of ACPL evaluation for each design

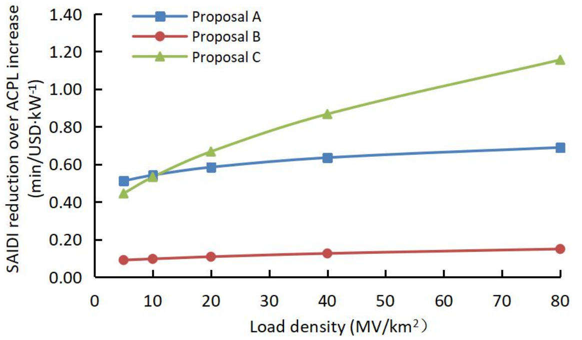


Figure 7. Results of cost-effectiveness analysis

Table 2. Statistical data for economic analysis

Component	Building investment (USD)	Annual operational cost (USD)
K-station	950,000	4,000
Cable (3×400mm²) per km	220,000	1,000
Cable (3×240mm²) per km	175,000	1,000
Cable (3×185mm²) per km	140,000	1,000
Ring main unit	75,000	500
MV/LV transformer	70,000	500
Differential protection	6,000	100
Optical fiber per km	4,000	100

V. CONCLUSIONS

Since the power service availability in Shanghai has already reached 99.99%, to further improve the reliability of distribution system it requires innovative ideas and apparently more investments. Three new network designs of K-stations have been brought up and analyzed in depth. Their advantages in reliability have been proven by the analysis model using the innovated Recursive Tree Algorithm. Given the average load density in Shanghai which is around 40MW/km², the analysis has indicated that Proposal A is the most effective one which reduces the system's interruption duration by 2.51% in the model, as Proposal B and C each reduces the duration by 1.08% and 1.83%. The costs required to achieve these improvements have been measured by increments of annul cost per load. With each extra dollar spent annually for each kW in the model, the annual SAIDI is expected to be reduced by 0.63, 0.13 or 0.87 minutes, depending on which proposal is chosen. Proposal A and C have shown better cost-effectiveness than Proposal B in general. Valuing the reliability improvement and taking the cost-effectiveness acceptable, grid managers in Shanghai have decided to put these proposals, especially Proposal A and C, into pilot practices.

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