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Evaluation of the variations of short-circuit capacities along a feeder due to distribution system-type upgrading

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ABSTRACT

The variations of short-circuit capacities (SCC's) along a feeder while a primary network is upgraded from original radial to normally closed loop arrangement is essential for examining the protection system of the network after upgraded. The increments of SCC's along a feeder may cause the existing protection devices installed at the original network and its customers' distribution systems becoming inadequate. Hence, a simple, systematic and straightforward evaluation method is required, especially in the planning stage. To meet these requirements the short-circuit MVA method was adopted in this paper. Based on the adopted method, the variations of SCC's along a primary feeder before and after the network upgraded were represented by simple formulas and illustrated by figures that make the variations more easily be recognized. The results not only are useful for engineers of utilities to better realizing the impact on the SCC's along feeder during the planning stage of network upgrading, but also confirm that the short-circuit MVA method is quite suitable for evaluating the variations of SCC's along a feeder.

1. Introduction

Nowadays, the high-tech, high value-added and energy–efficient industries had been developed rapidly in Taiwan. The sufficient, reliable and high quality power supply is, therefore, essential. New network arrangements should be considered because the two major primary network arrangements usually applied in Taiwan power company (Taipower), radial and normally open loop, are not qualified for serving these kinds of critical customers. Hence, a more reliable arrangement, the normally closed loop, was adopted and constructed to serve these sensitive loads about five year ago. At present, in Taipower's distribution systems, the radial arrangement is usually employed by the overhead feeders distributed in rural areas, and the normally open loop arrangement is utilized by the underground cables constructed in urban and suburban areas. According to the latest power outage statistics done by Taipower, most of the power outages that customers have experienced were due to faults occurring in distribution systems [1–3]. Furthermore, the statistics of the frequency and duration of customer outages in the Taipei city district of Taipower shows that the customer outages were mainly owing to faults occurring at the primary feeder. This major cause of customer outage accounted for more than forty percent of the total customer outages [4]. Accordingly, if we can ensure no service will be interrupted when a single fault occurs at the primary feeders, then the service reliability can be improved considerably. This is the major goal of Taipower at this time.

In general, a normally closed loop is designed so that no customers connected to the loop will be out of service when a fault occurs at the main feeder of the loop. Up to now, not only Taipower, but also, many other utilities in the world, such as Florida power company, Hong Kong electric company, and Singapore Power, have adopted normally closed loops to serve their critical customers [5,6]. Taipower is now planning to upgrade its distribution systems from original radials to normally closed loop arrangements extensively, especially in the science-based industrial parks, metropolitan areas and specific districts where higher service quality is required. This plan will noticeably improve the continuity of power supply and overall service quality.

Nevertheless, the impacts on the existing radial distribution systems and their customers while upgraded to normally closed loops should be evaluated in a detailed manner, especially during the planning and design stages. The variations of SCC's along the primary feeders should be evaluated first because their increment may result in the interruption capacities (ICs) of the existing protection devices becoming inadequate, and bring about a serious problem as well. It should be noted that the increment of SCC's along the feeders due to the configuration upgrading from original radial to normally closed loop is mainly depended on the arrange-

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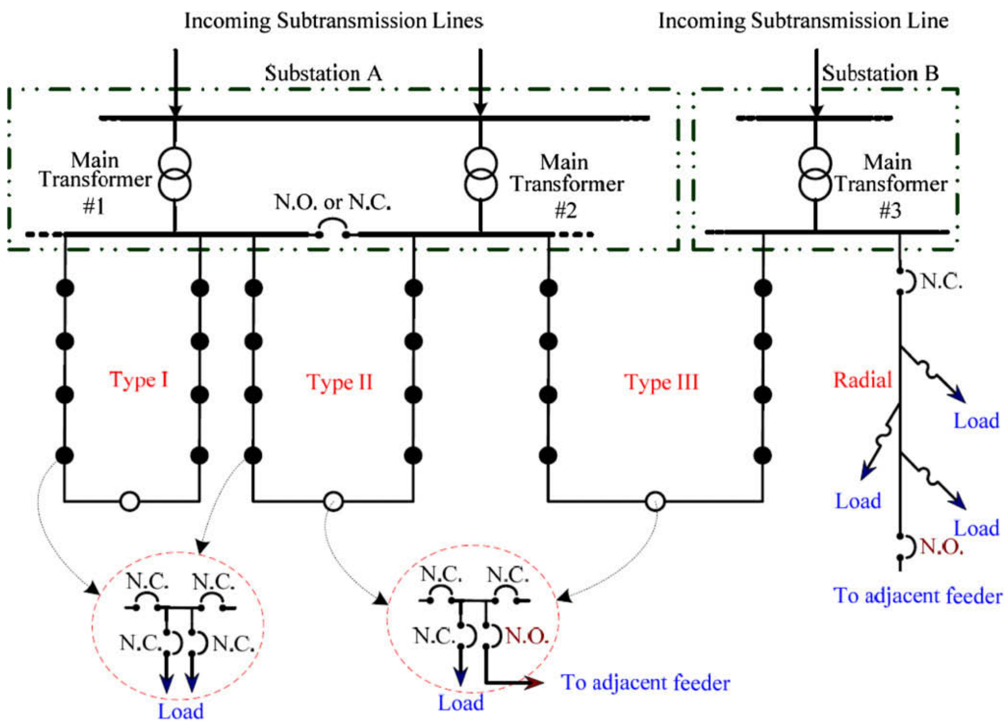

Fig. 1. Schematic diagram of three possible normally closed loop arrangements.

ment schemes of the closed loops. Fig. 1 illustrates a schematic diagram of three possible normally closed loop feeder arrangements. This figure shows that all the closed loop circuits have two sources. The major difference between these three arrangements is just the two sources. The difference makes the natures and reliabilities of these three types of arrangement quite different. The loop with Type I arrangement is the regular normally closed loop. The loop with Type II arrangement is an alternative to form a normally closed loop with better reliability. In addition, the loop with a Type III arrangement is actually an interconnection of two feeders served by two substations. Therefore, the variations of SCC's along the feeders while upgrading a distribution network from original radial to three types of normally closed loop arrangements are quite different and need to be explored. In this paper, the short-circuit MVA method was applied to evaluate the SCC's along the feeders for radial and three normally closed loop arrangements, and the factors that dominate the variation of SCC's along the feeders are analyzed and discussed in detailed. Finally, the comparisons of the increments of SCC's while upgrading a radial feeder to four normally closed loop arrangements were explored under various conditions. The outcomes are of value to the utilities that are planning to upgrade their distribution network configurations.

2. Problems and solving method

In this section, the problems and interested system structure with necessary parameters for fault analysis are introduced first, and followed by the introduction of the adopted solving method, the short-circuit MVA method.

2.1. Problem description

The short-circuit capacity (SCC) is defined as the product of the magnitude of total fault current of a three-phase short-circuit fault and the bus voltage before fault. It is a common measure of the strength of a bus, and is used for determining the interruption capacity of a circuit breaker as well as the dimension of a busbar. Generally, the strength of a busbar is decreasing gradually from generation to distribution systems for a vertical utility structure; therefore, the SCC's at a busbar in sub-transmission systems is usually higher than that of the distribution systems. Besides, because of the difference in locations and system structures, the SCC's are different even though at the same voltage level. That is the difference the incoming line, that is the distribution substations fed from sub-transmission systems, the SCC's at the primary side of the distribution substations are commonly not the same. Consequently, tying two radial primary feeders that fed from two power transformers located at two different distribution substations to form a normally closed loop will result in great variations of SCC's along distribution feeders. Moreover, the major factors that affect the SCC's along the feeders are the incoming line short-circuit duty, the rated capacities and impedances of the main transformers, the busbar schemes, the impedances of the conductors, as well as the fault location on the primary feeders. Hence, the variations of SCC's while upgrading two radial feeders to one normally closed loop feeder will be discussed in detailed in this paper by a systematic and straightforward method.

In this paper, the normally closed loop feeder arrangements are classified as Type I, II, and III, as shown in Fig. 1. Both normal and abnormal operating conditions are considered. Under normal operating condition, all circuit breakers (CB's) in the main loop of feeder are normally closed (N.C.), and the tie breakers to other feeders are normally opened (N.O.). The abnormal operating conditions mean the post-faulted operating conditions after relevance circuit breakers opening following a fault in the interested distribution system. In this paper, the faults are assumed occurring at the feeder main, secondary busbar of substation transformer, internal of substation transformer, and incoming sub-transmission line, separately. All the faults mentioned above will cause service interruption except the faults occurring at feeder main. Hence, the tie breaker should be closed automatically or manually to restore power for the interrupted customers after faults except the faults at feeder main. That is, the normally closed loop arrangement was designed to ensure no service will be interrupted when a single fault occurs at the feeder main, and temporary service interruption occurs for the faults at the secondary busbar of substation transformer, internal of substation transformer, and incoming sub-transmission line. Fig. 2 shows a sample primary distribution system for the evaluation of the variations of SCC's along a feeder. In this paper, the closed loop arrangements are classified as follows:

Type I: Two feeders, F#1 and F#2 are fed by the same power transformer and tied together normally at their ends to form a typical normally closed loop.

Type II: Two feeders are fed by two different transformers located in the same substation and tied together normally at their ends to form a cross-transformer-type normally closed loop. This type is further divided into two subtypes based on whether the tie breaker of the secondary buses of the two transformers is normally closed or open, as follows:

Type II.1: The tie breaker is normally open.

Type II.2: The tie breaker is normally closed.

Type III: The two feeders are fed by two different transformers located in different substations and tied together normally at their ends to form an interconnection-type normally closed loop.

In Fig. 2, the MVA_{sa} and MVA_{sb} represent the incoming line short-circuit duties of the two distribution substations *A* and *B*, respectively. The two substations are fed from different subtransmission circuits that are fed from different bulk power substations. The ratings of the three power transformers are assumed to be S_{T1}, S_{T2} and S_{T3}, and their corresponding impedances are Z_{T1}, Z_{T2} and Z_{T3}. The two main feeders are named as F#1 and F#2, and the tie line is named as TL. Because of the difference in system structures, the SCC's on the normally closed loops with different arrangements are quite different. The formulas for evaluating the SCC's along a feeder will be derived in the following section. The SCC's along a feeder are functions of the incoming line short-circuit duties, the rated capacities and impedances of the power transformers and the impedances of the feeders. Next, the SCC's along a primary feeder for various network arrangements under various system conditions will be illustrated by curves. The effect of each system parameter mentioned above on the SCC's along a feeder can therefore be easily realized. Finally, the variations of SCC's along a feeder of various primary network arrangements were compared, and the impacts of upgrading primary network from radial to normally closed loop on the system and their customers can therefore be explored.

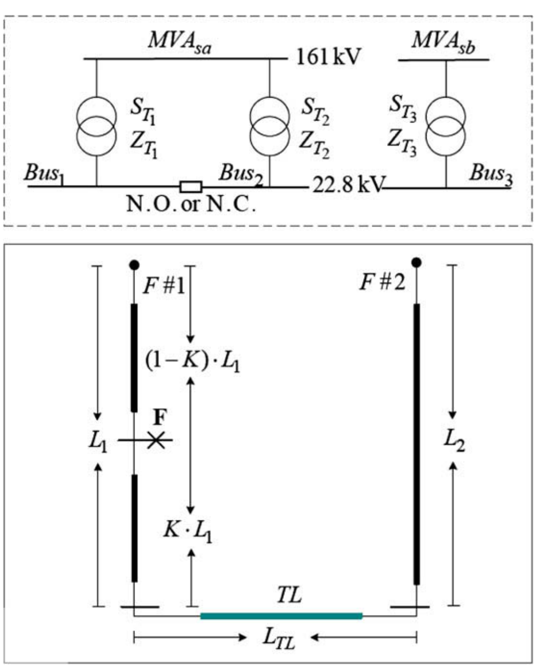

Fig. 2. A sample primary distribution system for studying.

2.2. Short-circuit MVA method

The MVA method is a modification of the Ohmic method [7]. As shown in Fig. 3, the MVA method is used by separating the circuit into components, and calculating the short-circuit MVA of each component with its own infinite bus. Therefore, the first step of the short-circuit MVA method is converting all the related components into their corresponding short-circuit MVA's. As for the generators, motors, and transformers, the conversion formula is as follows:

$$MVA_{SC} = \frac{S_{Rated}(MVA)}{Z_{pu}} \tag{1}$$

In addition, the conversion formula for the conductor is

$$MVA_{SC} = \frac{KV_L^2}{Z_\Omega}(MVA) \tag{2}$$

Where subscripts 'sc', 'Rated', 'pu' and 'Ω' refer to short-circuit, rated capacity, per unit, and ohm, respectively.

An MVA diagram is developed after all the components were converted into their corresponding short-circuit MVA's. The second step is to reduce the MVA diagram. The parallel and series MVA combinations, as shown in Fig. 4, must be calculated by (3) and (4), respectively. Finally, the short-circuit MVA at the fault point is calculated. This method for short-circuit studies of distribution systems is easy-to-learn and easy-to-use. Furthermore, a modified method, complex short-circuit MVA method has been proposed for power system studies [8,9]. In this paper, the short-circuit MVA method was used to formulate the SCC at the fault point for various feeder arrangements and correlative parameters.

$$MVA_{SC}^{Parallel} = \sum_{i=1}^{n} MVA_{SC}^{i} \tag{3}$$

$$MVA_{SC}^{Series} = \left[\sum_{i=1}^{n} \frac{1}{MVA_{SC}^{i}}\right]^{-1} \tag{4}$$

where superscripts '*i*' refer to the *i* th component of the system.

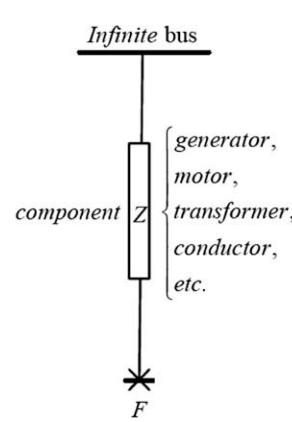

Fig. 3. Scheme for calculating short-circuit MVA of individual elements.

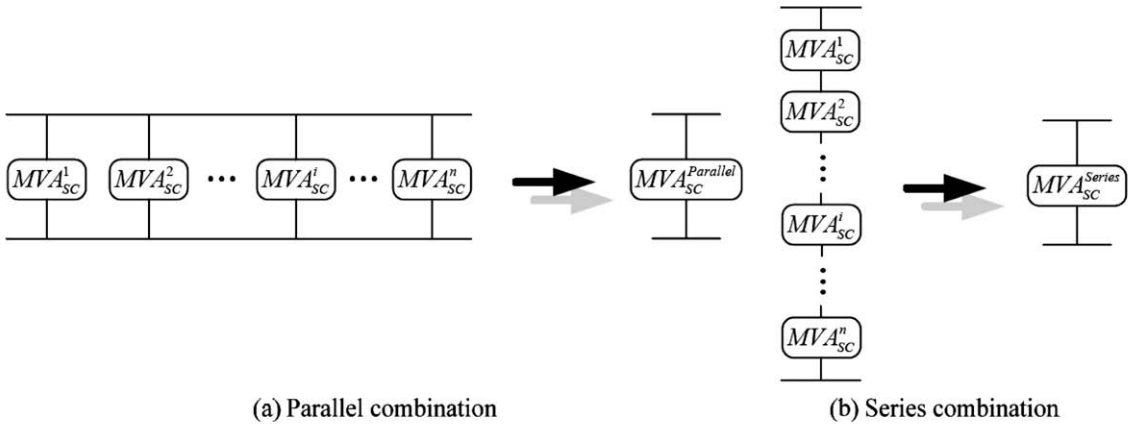

Fig. 4. Parallel and series combinations.

A normalized short-circuit capacities shown in (5) was applied in this paper to represent the variations of SCC's along a feeder caused by primary network upgrading.

$$\text{S.C.C.}_{\text{norm}} \equiv \frac{\text{MVA}^{F}_{\text{SC, System Type}}}{\text{MVA}^{F}_{\text{SC, Radial}}} \quad (5)$$

Where

$\text{S.C.C.}_{\text{norm}}$ is the normalized short-circuit capacity.

$\text{MVA}^{F}_{\text{SC, System Type}}$ is the SCC's along a feeder for three type of normally closed loop arrangement.

$\text{MVA}^{F}_{\text{SC, Radial}}$ is the SCC's along a feeder for original radial arrangement.

3. Mathematical analysis and discussion

In this paper, the short-circuit MVA method was used to evaluate the SCC's along a feeder. Therefore, the short-circuit MVA of each equipment, such as generators, transformers, motors, feeders, etc. needs to be found first. For practical purposes, the sample system was designed according to an actual underground distribution system of Taipower in an urban area with little modification.

Table 1 lists the parameters of the sample distribution system required for the evaluation of the SCC's. The transformer capacities, the nominal voltage of the primary system, the line reactance of the feeders, and the length of tie line were all kept constant in the following discussions. Noted that reactances only are considered in the studying cases. It is felt that using impedances would give almost the same result, but would complicate the calculations.

For the base case, incoming line short-circuit duties (at the primary side of distribution substations) are assumed to be 5000 MVA. They are normally given by a power company. The lengths of the feeder cables are all assumed to be 10 km, and the per unit reactances of the three main transformers are assumed 0.1672 pu. In the following subsections, these parameters will be changed in reasonable ranges to examine the effects of each parameter under various feeder arrangements.

As conversion was made, Table 2 and an MVA diagram were developed. Referring to the MVA diagram, the short-circuit MVA's of all equipments were combined. The series MVA's were combined as resistances in parallel, and the parallel MVA's were added arithmetically. Finally, the short-circuit MVA' of the fault point was found. The short-circuit MVA method does make the calculation of short-circuit current more straightforward and easy.

For comparison, the SCC's along the primary feeders for various network arrangements, such as radial and three types of normally closed loops, were evaluated. Finally, the increments of the SCC's along a feeder due to network upgrading were compared by the SCC curves. These curves make the impacts of system upgrading from original radial to normally closed loop arrangement with different correlative parameters and connection schemes more clear.

3.1. Radial arrangement

For the system shown in Fig. 2, if the feeder F#1 is connected to bus 1, and the two tie breakers, one located between the secondary busbars of two main transformers and the other at its end are open, then the feeder F#1 is radial. The MVA diagram of this radial arrangement was shown in Fig. 5. Assume a three-phase fault occurs at a point on the main feeder at a distance of $(1-k)L_1$ m from the feed point, only series MVA combination is required. And the SCC at the fault point can be expressed as

$$\text{MVA}^{F}_{\text{SC, Radial}} = \left[\frac{1}{\text{MVA}_{\text{sa}}} + \frac{1}{\text{MVA}_{T_1}} + \frac{1}{\text{MVA}_{(1-K)L_1}}\right]^{-1} \quad (6)$$

where

MVA_{sa} is the incoming line short-circuit duty on the primary side of the substation transformer A.

MVA_{T_1} is the corresponding short-circuit MVA of the main transformer #1.

$\text{MVA}_{(1-K)L_1}$ is the short-circuit MVA of the feeder segment between the fault point (any location on the main feeder)

Table 1
Parameters of the sample distribution system.

Parameters	Variables	Base case	Ranges (%)
Incoming line short-circuit duties	MVA_{sa}, MVA_{sb}	5000 MVA	20–200
Transformer capacities	S_{T1}, S_{T2}, S_{T3}	60 MVA	100
Transformer impedances	Z_{T1}, Z_{T2}, Z_{T3}	0.1672 pu	90–110
Feeder lengths	L_1, L_2	10 km	20–200
Tie line length	L_{TL}	0.3 km	100
Feeder impedances	Z_{Ω}	0.1795 Ω/km	100

Table 2
Corresponding short-circuit MVA of each equipment.

Equipment	Base case (MVA)	Ranges (MVA)
MVA_{sa}, MVA_{sb}	5000	1000–10,000
MVA_{T1}, MVA_{T2}, MVA_{T3}	359	326–399
MVA_{L1}, MVA_{L2}	290	145–1448
MVA_{TL}	9653	9653

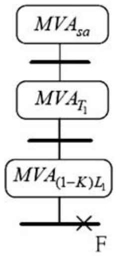

Fig. 5. MVA diagram of radial arrangement.

and feed point (the secondary busbar of the main transformer)

K: variable from 1 to 0, for indicating the fault location

Substituting (1) and (2) into (6), the SCC of the fault point on the radial feeder can be formulated as

$$\mathrm{MVA}^{F}_{\mathrm{SC,\,Radial}} = \left[\frac{1}{\mathrm{MVA_{sa}}} + \frac{Z_{\mathrm{T_1(pu)}}}{S_{\mathrm{T_1}}} + \frac{(1-K)L_1 Z_\Omega}{\mathrm{KV}_L^2}\right]^{-1} \tag{7}$$

Based on (7), the SCC curves were developed as shown in Fig. 6. The SCC curves relate the incoming line short-circuit duty, transformer impedance and the fault location. There are five curves in Fig. 6. The solid curve shows the SCC's along the feeder F#1 under the conditions of base case. The other four curves show the deviations of the corresponding SCC's from the base case for two values of the incoming line short-circuit duties and two values of the transformer impedances. The smaller the incoming line short-circuit duty or the greater the transformer impedance is, the smaller the corresponding SCC's obtained, as shown in Fig. 6. These two factors predominantly affect the SCC's along the feeder. As usual, the farther the fault point at the primary feeder is, the smaller the corresponding SCC obtained. Fig. 6 also shows that the farther the fault point at the primary feeder is, the smaller the deviations of corresponding SCC obtained. That means the effect of the incoming line short-circuit duty and the transformer impedance on the SCC's along a feeder is the largest in the feed point and the smallest in the end of the feeder. This is because the $\mathrm{MVA}_{(1-K)L_1}$ is relatively smaller when the fault point is far away from the feed point.

3.2. Closed loop arrangement

(1) Type I: The MVA diagram of a normally closed loop arrangement of Type I was shown in Fig. 7. Assumed fault occurs at a point on the main feeder at a distance of $(1-k)L_1$ m from the feed point, the SCC at the fault point can be expressed as

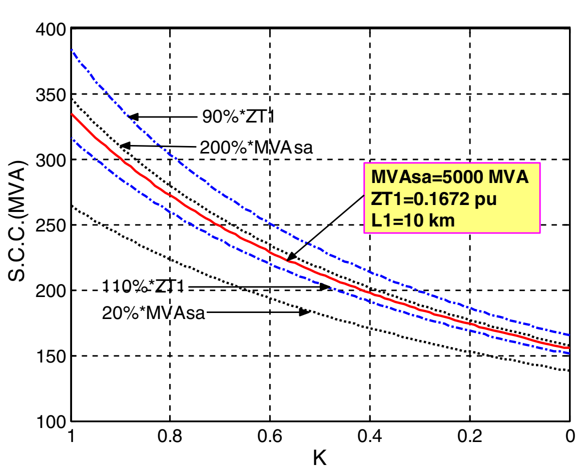

Fig. 6. SCC versus fault location for radial arrangement.

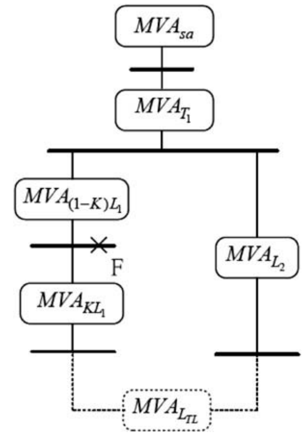

Fig. 7. MVA diagram of a normally closed feeder arrangement of Type I.

$$\mathrm{MVA}^{F}_{\mathrm{SC,\,TypeI}} = \left\{ \begin{array}{l} \frac{1}{\mathrm{MVA_{sa}}} + \frac{1}{\mathrm{MVA_{T_1}}} \\ + \left[\mathrm{MVA}_{(1-k)L_1} + \left(\frac{1}{\mathrm{MVA}_{KL_1}} + \frac{1}{\mathrm{MVA}_{L_{\mathrm{TL}}}} + \frac{1}{\mathrm{MVA}_{L_1}}\right)^{-1}\right]^{-1} \end{array} \right\}^{-1} \tag{8}$$

Where

$\mathrm{MVA}^{F}_{\mathrm{SC,\,TypeI}}$ is the SCC's along the primary feeder of Type I arrangement.

Similarly, Substituting (1) and (2) into (8), the SCC's along the primary feeder of Type I arrangement can be formulated as

$$\mathrm{MVA}^{F}_{\mathrm{SC,\,TypeI}} = \left\{ \begin{array}{l} \frac{1}{\mathrm{MVA_{sa}}} + \frac{Z_{\mathrm{T1(pu)}}}{S_{\mathrm{T1}}} \\ + \left[\frac{KV_L^2}{(1-K)L_1 Z_\Omega} + \frac{KV_L^2}{(KL_1+L_{\mathrm{TL}}+L_2)Z_\Omega}\right]^{-1} \end{array} \right\}^{-1} \tag{9}$$

Based on (9), seven SCC curves, relating the incoming line short-circuit duty, transformer impedance, the length of feeder F#2 and the fault location, have been developed, as shown in Fig. 8. The solid curve show the SCC's along the feeder F#1 under the conditions of base case. The other six curves show the deviations of the corresponding SCC's from the base case for two values of the incoming line short-circuit duties, two values of the transformer impedances and two values of the lengths of feeder F#2. The effects of the incoming line short-circuit duty and the transformer impedance are the same as that of the feeder with radial arrangement. The effects of the incoming line short-circuit duty and the transformer impedance on the SCC's along the feeder F#1 is the largest in the feed point and the smallest in the end of the feeder. On the contrary, the effects of the length of feeder F#2 on the SCC's along the feeder F#1 is the smallest in the feed point and the largest in the end of the feeder.

The only difference between radial and Type I closed loop arrangement is the feeder structure. For the closed loop arrangement, there are two sources contribute the fault current. However, there is only one source contributes the fault current for the radial arrangement. For this reason, the SCC's along the primary feeder get higher moderately when the feeder arrangement is upgraded from radial to normally closed loop. The increment of the SCC's along the feeder F#1 due to network upgrading mainly depend on the length of the two tied feeders F#1 and F#2. Generally, the shorter the length the feeder F#2 is, the more the increment of the SCC's along the feeder F#1 obtains.

(2) Type II.1: The MVA diagram of a normally closed loop arrangement of Type II.1 was shown in Fig. 9. According to the system structure, the SCC's along the Feeder #1 can be represented as

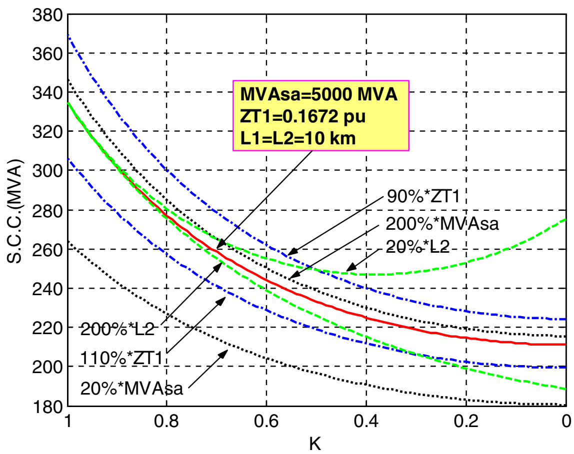

Fig. 8. SCC's versus fault location for a normally closed feeder arrangement of Type I.

$$\mathrm{MVA}^F_{\mathrm{SC,\,TypeII.1}} = \left\{ \frac{1}{\mathrm{MVA_{sa}}} + \left[\left(\frac{1}{\mathrm{MVA}_{T_1}} + \frac{1}{\mathrm{MVA}_{(1-K)L_1}}\right)^{-1} + \left(\frac{1}{\mathrm{MVA}_{T_2}}+\frac{1}{\mathrm{MVA}_{L_2}} + \frac{1}{\mathrm{MVA}_{L_{TL}}} + \frac{1}{\mathrm{MVA}_{KL_1}}\right)^{-1}\right]^{-1}\right\}^{-1} \quad (10)$$

Substituting (1) and (2) into (10) yields

$$\mathrm{MVA}^F_{\mathrm{SC,\,TypeII.1}} = \left\{ \frac{1}{\mathrm{MVA_{sa}}} + \left[\left(\frac{Z_{T_1(\mathrm{pu})}}{S_{T_1}} + \frac{(1-K)L_1 Z_\Omega}{KV_L^2}\right)^{-1} + \left(\frac{Z_{T_2(\mathrm{pu})}}{S_{T_2}} + \frac{(L_2+L_{TL}+KL_1)Z_\Omega}{KV_L^2}\right)^{-1}\right]^{-1}\right\}^{-1} \quad (11)$$

Based on (11), seven SCC curves were developed as shown in Fig. 10. The profiles of the curves in Fig. 10 are similar to the corresponding curves shown in Fig. 8. However, the levels of the SCC's are all going up and the effects of the factors are enlarged.

(3) *Type II.2*: The MVA diagram of a normally closed loop arrangement of Type II.2 was shown in Fig. 11. According to the system structure, the SCC's along Feeder #1 can be represented as

$$\mathrm{MVA}^F_{\mathrm{SC,\,TypeII.2}} = \left\{ \frac{1}{\mathrm{MVA_{sa}}} + (\mathrm{MVA}_{T_1} + \mathrm{MVA}_{T_2})^{-1} + \left[\mathrm{MVA}_{(1-K)L_1} + \left(\frac{1}{\mathrm{MVA}_{L_2}} + \frac{1}{\mathrm{MVA}_{L_{TL}}} + \frac{1}{\mathrm{MVA}_{KL_1}}\right)^{-1}\right]^{-1}\right\}^{-1} \quad (12)$$

Eq. (12) can be rewritten as

$$\mathrm{MVA}^F_{\mathrm{SC,\,TypeII.2}} = \left\{ \frac{1}{\mathrm{MVA_{sa}}} + \left(\frac{S_{T_1}}{Z_{T_1(\mathrm{pu})}} + \frac{S_{T_2}}{Z_{T_2(\mathrm{pu})}}\right)^{-1} + \left[\frac{KV_L^2}{(1-K)L_1 Z_\Omega} + \frac{KV_L^2}{(L_2+L_{TL}+KL_1)Z_\Omega}\right]^{-1}\right\}^{-1} \quad (13)$$

Based on (13), seven SCC curves were developed as shown in Fig. 12. The profiles of the curves in Fig. 12 are similar to the corresponding curves shown in Fig. 10. However, the levels of the SCC's are all going up because the two transformers were operated parallel in this arrangement.

(4) *Type III*: The MVA diagram of a normally closed loop arrangement of Type III was shown in Fig. 13. According to the system structure, the SCC's along the Feeder #1 can be represented as

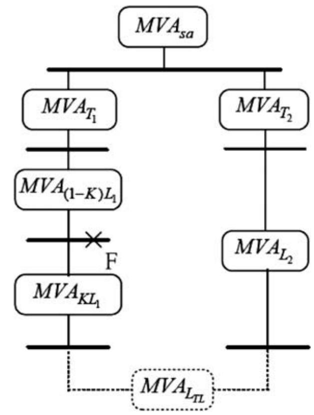

Fig. 9. MVA diagram of a normally closed feeder arrangement of Type II.1.

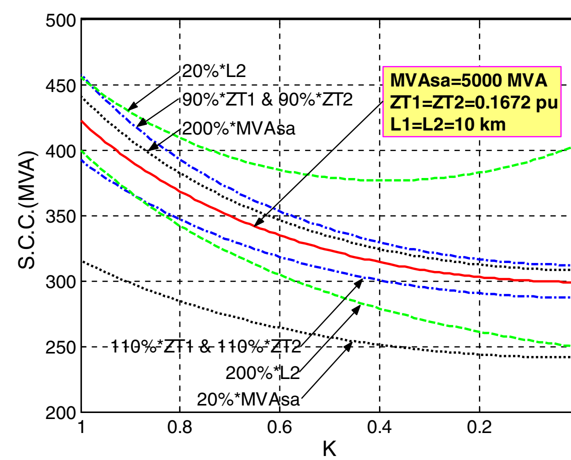

Fig. 10. SCC's versus fault location for a normally closed feeder arrangement of Type II.1.

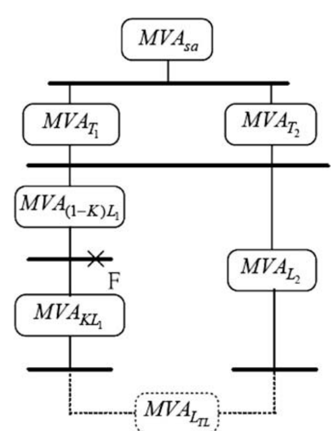

Fig. 11. MVA diagram of a normally closed feeder arrangement of Type II.2.

$$\mathrm{MVA}^F_{\mathrm{SC,\,TypeIII}} = \left(\frac{1}{\mathrm{MVA_{sa}}} + \frac{1}{\mathrm{MVA}_{T_1}} + \frac{1}{\mathrm{MVA}_{(1-K)L_1}}\right)^{-1} + \left(\frac{1}{\mathrm{MVA_{sb}}} + \frac{1}{\mathrm{MVA}_{T_3}} + \frac{1}{\mathrm{MVA}_{L_2}} + \frac{1}{\mathrm{MVA}_{L_{TL}}} + \frac{1}{\mathrm{MVA}_{KL_1}}\right)^{-1} \quad (14)$$

Rewritten (14) as

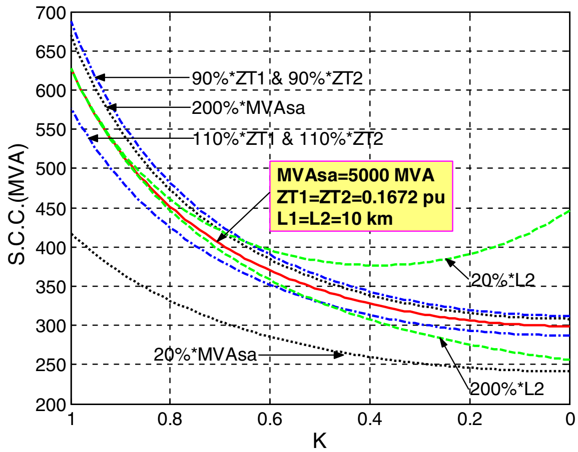

Fig. 12. SCC's versus fault location for a normally closed feeder arrangement of Type II.2.

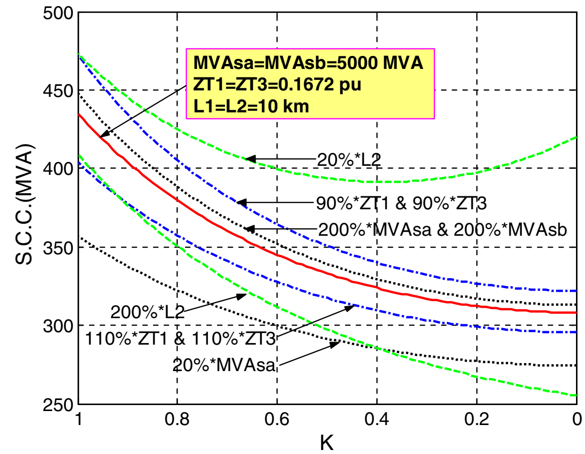

Fig. 14. SCC's versus fault location for a normally closed feeder arrangement of Type III.

$$\mathrm{MVA}^{F}_{\mathrm{SC,\,TypeIII}} = \left(\frac{1}{\mathrm{MVA_{sa}}} + \frac{Z_{\mathrm{T_1(pu)}}}{S_{\mathrm{T_1}}} + \frac{(1-K)L_1 Z_\Omega}{KV_L^2}\right)^{-1} + \left(\frac{1}{\mathrm{MVA_{sb}}} + \frac{Z_{\mathrm{T_3(pu)}}}{S_{\mathrm{T_3}}} + \frac{(L_2+L_{\mathrm{TL}}+KL_1)Z_\Omega}{KV_L^2}\right)^{-1} \quad (15)$$

Based on (15), seven SCC curves were developed as shown in Fig. 14. The profiles of the curves in Fig. 14 are similar to the corresponding curves shown in Fig. 10.

Because two tied feeders are fed by two main transformers located at different distribution substations, the SCC's along a feeder after the two feeders were tied together to form a closed loop will mainly functions of the SCC's along a feeder when the two feeders remain radial.

4. Comparison and discussion

In order to sum up the results of numerical analysis presented in Section 3, and make clear the effects of distribution network upgrading on the SCC's along a feeder, two comparison figures containing six subgraphs have been plotted in this section. Fig. 15 shows the effect of distribution network upgrade from radial to normally closed loop arrangement on the SCC's along a feeder. The SCC curves shown in Fig. 15a were obtained under the conditions of base case as described in Table 1. For realizing easily the increment of the SCC's along a feeder, five SCC curves for five

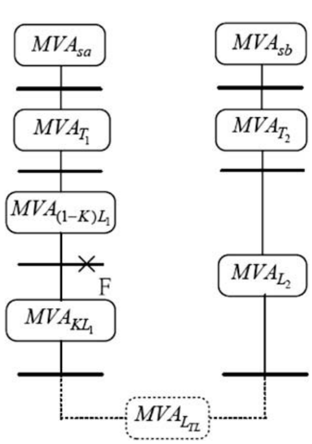

Fig. 13. MVA diagram of a normally closed feeder arrangement of Type III.

network arrangements were all divided by their corresponding SCC's of the radial arrangement (solid curve) as shown in Fig. 15b. Fig. 15b indicates that the SCC's at the feeder end for Type II.1, II.2 and III arrangements are almost double the corresponding SCC of the radial arrangement. However, the Type I arrangement is not the case. Hence, the effect on the SCC's along a feeder is limited, and all the existing customer's protection devices and their settings still work and no change is required when a distribution network is upgraded to normally closed loop with Type I arrangement. The Type I arrangement has been recommended to Taipower by the authors of this paper and been accepted by Taipower. At least five Taipower districts have constructed this kind of normally closed loop up to now.

Furthermore, Fig. 15b also shows that the incremental rates of the SCC's along a feeder of Type II.2 arrangement is usually the largest among the four kinds of arrangements for the entire feeder. It is noted that the results shown in Fig. 15 were obtained under the conditions of a special case, the base case. If this is not the case, the SCC's along a feeder will change as usual. Fig. 16 indicates the effects of major factors on the SCC's along a feeder. Some conditions were changed to explore their effects on the SCC's along a feeder. All the factors were varied in a reasonable range as listed in Table 1. Four cases were used to demonstrate the effects of the major factors on the SCC's along a feeder for various network arrangements. More, for realizing easily the variations of the SCC's along a feeder due to a distribution network upgrading, the SCC's along a feeder for four normally closed loop arrangements were all divided by their corresponding SCC's of the radial arrangement. The four cases are presented below:

Case #1: This case is used to demonstrate the effect on the SCC's along a strong feeder (with larger SCC's along the feeder before tied) while the strong feeder were tied with a weak feeder (with smaller SCC's along the feeder before tied) to form a normally closed loop. Five SCC curves outlining the SCC's along the strong feeder, Feeder #1, for five network arrangements were plotted in Fig. 16a. To enlarge the differences between these two tied feeders, the incoming line short-circuit duties of substation A and B are respectively set to 200% and 20% of the base case, i.e. 10,000 MVA and 1000 MVA, respectively; the lengths of the feeder #1 and #2 are respectively set to 20% and 200% of the base case, i.e. 2 km and 20 km, respectively; and the impedances of transformer #1, #2 and #3 are respectively set to 90%, 90% and 110% of the base case, i.e. 0.16729 pu, 0.16729 pu and 0.18402 pu, respectively. Fig. 16a illustrates that the incremental rates of the Type II.2 arrangement is the largest among the four closed loop arrange-

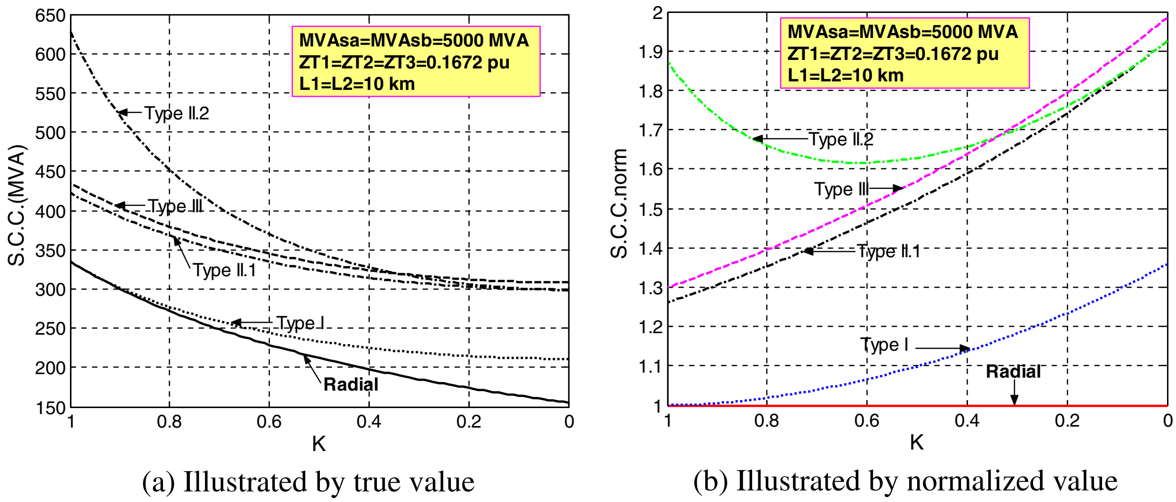

Fig. 15. SCC's versus fault location for each feeder arrangement of the base case.

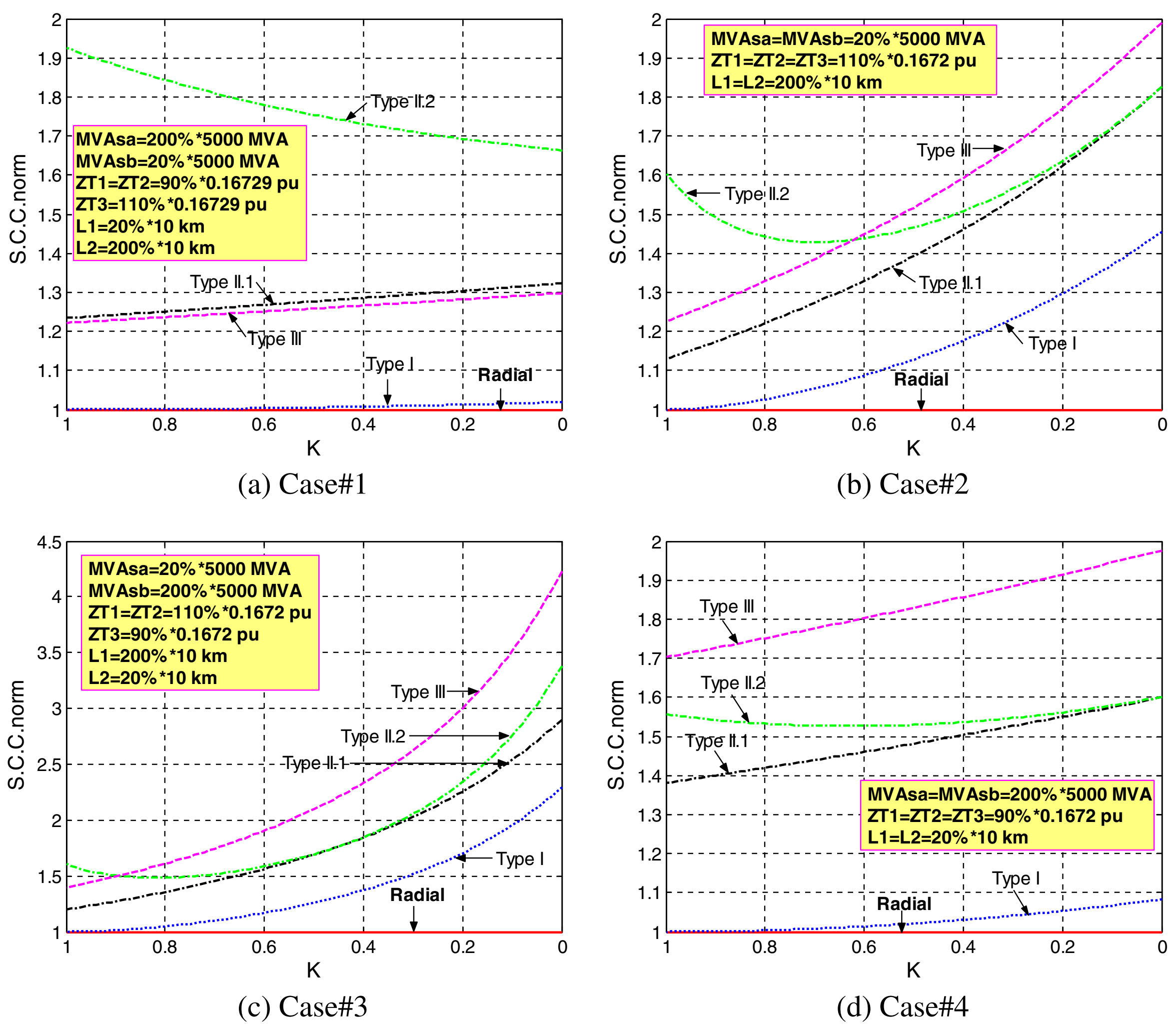

Fig. 16. Comparisons of SCC's versus fault location among each feeder arrangement normalized by radial type.

ments, the incremental rates of Type II.1 and III arrangements are almost the same, and the incremental rate of the Type I arrangement is the smallest among the four arrangements. It is noted that the incremental rates of Type I arrangement is very small and can be ignored in general. More, the effect of the lengths of the two tied feeders on the SCC's along the feeder are not considerable so the spread of the incremental rates of the SCC's along a feeder is not large in this case.

Case #2: This case is used to demonstrate the effect on the SCC's along the feeder while two weak feeders were tied together to form a normally closed loop. Fig. 16b illustrates that the largest incremental rates are no longer the Arrangement II.2 at least for the latter 60% of the feeder, the incremental rates of the Type III arrangement become the largest among the four arrangements in the latter 60% of the feeder; the incremental rates of Arrangement Type II.1 and II.2 are closed at the later 40% of the feeder and diverge at the other portion; and the incremental rates of Type I arrangement is still the least among the four closed loop arrangements. More, the incremental rates of Type I arrangement are not small enough and therefore can not be ignored in this case. It is noted that the effect of the lengths of the two tied feeders on the SCC's along the feeder are now considerable in this case.

Case #3: This case is used to demonstrate the effect on the SCC's along the weak feeder while a weak feeder were tied with a strong feeder to form a normally closed loop. Five SCC curves sketching the SCC's along the weak feeder for five network arrangements were shown in Fig. 16c. Fig. 16c illustrates that the incremental rates of the Type III arrangement is the largest among the four closed loop arrangements, the incremental rates of Arrangement Type II.1 and II.2 are almost the same at the middle part of the feeder, and the incremental rates of the Type I arrangement are still the least among the four closed loop arrangements. However, it should be noted that the incremental rates of Type I arrangement are now considerable and can not be ignored.

Case #4: This case is used to demonstrate the effect on the SCC's along the feeder while two strong feeders were tied together to form a normally closed loop. Five SCC curves outlining the SCC's along the feeder for five network arrangements were shown in Fig. 16d. Fig. 16d also illustrates that the incremental rates of the Type III arrangement are the largest among the four closed loop arrangements, the incremental rates along the later half of the feeder of Type II.1 and II.2 arrangement are very closed, and the incremental rates of Type I arrangement are still the least among the four closed loop arrangements. More, the incremental rates of Type I arrangement are quite small and can be ignored. More, the incremental rates of the SCC's along the feeder are increased generally from the feed point to the feeder end.

It is obvious that the variations of SCC's along a normally closed loop feeder with Type I arrangement are the smallest among the three types arrangements discussed above. However, it should be noted that in order to ensure no service will be inturrepted when a single fault occurs at the feeder main, all the LBSs in the main loop circuit should be replaced by CBs with required proper interrupting capacities and communication facilities. Moreover, a more complex relaying system with intelligent electronic devices (IEDs) and functions of permissive overreaching transfer trip (POTT) and directional comparison blocking (DBC) are also necessary. The detailed protection schemes for a normally closed loop have been addressed in [10,11].

5. Conclusions

In this paper, a simple, straightforward and planning-oriented method, the short-circuit MVA method, was applied to evaluate the increments of SCC's along primary feeders while a distribution network was upgraded from original radial to a normally closed loop arrangement. The SCC curves representing the SCC's along a feeder for various network arrangements were plotted easily based on the formulas obtained by the short-circuit MVA method. Some major factors of the short-circuit capacity, such as the incoming line short-circuit duty, the feeder length, and the transformer impedances are considered. Hence, the derived formulas are all functions of these three major factors. The SCC evaluation formulas and the SCC curves make clear the variations of network upgrading and are of value to the relevant engineers for better realizing the impacts on the SCC's along the feeder, especially during the planning stage of network upgrading.

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