Feasibility Study of Upgrading Primary Feeders From Radial and Open-Loop to Normally Closed-Loop Arrangement

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***Abstract*—The feasibility study of upgrading primary feeders from radial and open loop to a normally closed-loop arrangement have been explored in this paper. First, three possible feeder arrangements for forming a normally closed loop are discussed, and then the factors that may predominantly affect the system-type upgrading are discussed theoretically. Next, four existing distribution feeders with original radial arrangements, fed by three power transformers that are located at two different distribution substations of Taiwan Power Company (Taipower) are employed as sample systems. To form three types of closed-loop arrangement, all of the four radial feeders were tied together at their ends, two feeders at a time. The power flows, voltage profiles and short-circuit capacities of the feeders under both the tie breaker normally open and closed cases have been evaluated, and the impacts of the upgrading of system type on the distribution system and customers assessed. Finally, the required supporting measures for these kinds of upgrading have been listed, and the most suitable and feasible arrangement was recommended to Taipower.**

***Index Terms*—Distribution system, normally closed loop, open loop, primary feeder, radial.**

I. INTRODUCTION

IN THE EARLY 1980s, the Taiwan government began to focus on the strategic development of high-tech, high value-added and energy-efficient industries. The successful establishment of the Hsinchu Science-Based Industrial Park had a significant impact on Taiwan's high-tech industries. By 1990, high-tech products, mainly electronics, information and machinery products, accounted for 40.2% of the total exports of Taiwan. Sufficient, reliable and high quality power supply is therefore essential. Nowadays, more and more high-rise buildings have appeared in the urban areas of Taiwan. The living standards in these areas have considerably improved in recent years. Reliable and high quality power supply is therefore more vital than ever. Some customers cannot afford either a short-period interruption or a long-duration voltage dip.

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TABLE I
THE FREQUENCY AND DURATION OF CUSTOMER OUTAGES IN TAIPEI CITY DISTRICT OF TAIPOWER

Items	Frequency of Customer Outages		Duration of Customer Outages	
Events	Frequency	%	Min	%
Feeder Cable	27345	45.6	1077853	41.6
High Voltage Switch	13999	23.4	474201	18.3
Cable Connection	15000	25	649483	25
Distribution Transformer	3087	5.2	347978	13.4
Service Drop	189	0.3	7730	0.3
Secondary Conductor	323	0.5	36898	1.4
Total	59943	100	2594143	100

Even though there are many fold approaches to increasing the reliability of existing radial or open-loop primary feeders, such as various sectionalizing and load-transfer facilities used to limit the effects of primary distribution network faults [1]–[4] etc., momentary interruptions still exist while a fault occurs.

In practice, most of the power outages that customers have experienced were due to faults occurring in distribution systems [5]. Table I indicates the statistics of the frequency and duration of customer outages in the Taipei City District of Taipower. The statistics 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. If we can make sure no service will be interrupted when a single fault occurs at the primary feeder, then service reliability can be improved considerably. This is the major goal of Taipower at present.

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 feeder main of the loop. To reach this goal the protection system should be upgraded as well. All the load-break switches (LBSs) should be replaced by circuit breakers (CBs) with interruption capacity of short-circuit current. 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 customers [6], [7].

Taipower is now planning to upgrade its distribution systems from original radial or open-loop to a normally closed-loop arrangement broadly, 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.

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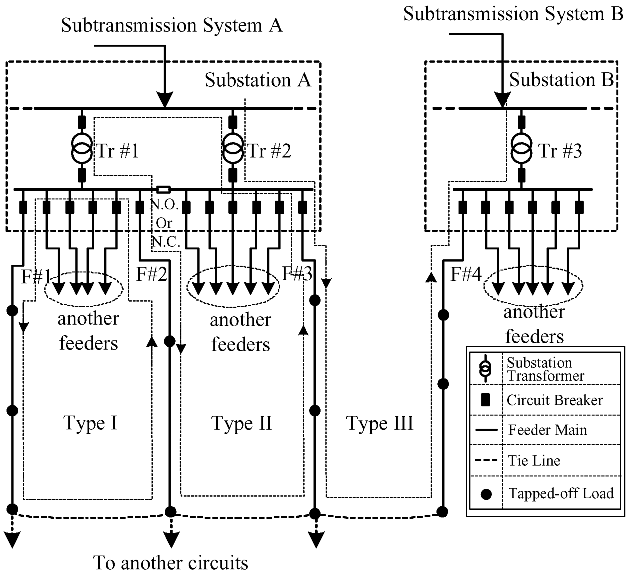

Fig. 1. Schematic diagram of three possible arrangements for forming a normally closed-loop feeder.

The impacts on the existing systems and customers while upgrading should be evaluated in a detailed manner, especially during feasibility study. This paper deals with the upgrading techniques and impacts. Four feeders fed from two distribution substations of Taipower in downtown Taipei were used as the sample feeders. To explore the impacts of system upgrading, some detailed analyzes have been performed in addition to the basic engineering analyzes. Based on the basic and extra engineering analyzes, the impacts can therefore be explored and the required supporting measures can be drawn.

In this upgrading project, the fundamental and most important consideration is the impact on the original system and customers. The customer outage costs and the cost of replacing all the LBSs with CBs and constructing a feeder automation system with high speed communications between the protective relays at each CB were all considered before the project was conducted. But the detailed economic analysis and reliability assessment will not presented in this paper. The resulting reliability improvement from implementing closed-loop feeder arrangements is quite obvious, therefore, no information about the reliability assessment was presented in this paper.

II. Upgrading of Feeder Arrangement

A. Feeder Arrangements

A normally closed loop can be formed by tying the ends of two radial feeders together. Fig. 1 illustrates a schematic diagram of three possible normally closed-loop feeder arrangements [8]. 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 closed-loop arrangements are classified as follows.

Type I: The two feeders for forming a closed loop were fed by the same power transformer.

Type II: The two feeders for forming a closed loop were fed by two different transformers located in the same substation. This type is further divided into two subclasses based on whether the tie breaker of the secondary buses of the two transformers is 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 for forming a closed loop were fed by two different transformers located in different substations.

The natures and reliabilities of these three types of arrangement are 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.

B. Basic Considerations

In general, the characteristic of an open-loop feeder is the same as that of a radial feeder, except during the load transfer period. For simplicity, only the upgrading from radial to normally closed-loop arrangement has been discussed in this paper.

Many factors should be considered while upgrading the feeder arrangement to a normally closed loop by tying the ends of two existing radial feeders together, such as:

- the short-circuit currents, capacities and voltage levels of the substations;
- the ratings, impedances, loadings, and load characteristics of the substation transformers;
- the size, length, loading, load distribution, and load characteristics of the feeders.

Not only the qualities of these factors, but also their variations in different operation conditions, are important. These factors affect, considerably, both normal and abnormal operations of closed-loop feeders. The capacities of substation transformers, the ampacities of conductors, the voltage profiles along the feeders, the ratings and settings of protective devices, etc. should all be examined to make sure the entire system is well designed while operated in a normally closed-loop arrangement. On this basis, the feasibility of system-type upgrading is discussed in detail as follows.

1) Type I: In Fig. 1, two radial feeders F#1 and F#2 fed by the same power transformer were tied together at their ends to form a typically normally closed-loop feeder, classified as type I in this paper. The factors affecting this kind of upgrading are:

- the conductor sizes of the feeders;
- the lengths of the feeders;
- the loadings of the feeders;
- the distribution of the loads along the feeders;
- the characteristics of the loads along the feeders.

Hence, the natures of feeders are the key factor for successfully upgrading a system type from radial to type I closed-loop arrangement.

In general, primary feeders are classified as thermally limited feeders (TL feeders) and voltage-drop-limited feeders (VD feeders). The feeders serving the customers in urban or suburban areas, having short lengths and high load densities, therefore,

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belong to the class of TL feeder. For example, the feeders in the urban areas of Taipei have lengths approximately 2 km or less, and they usually are operated under heavy loading conditions, their utilization factors are usually over 80%. In this case, the loading of this kind of feeder is the key factor and must be considered and reduced to meet the requirement of forming a normally closed loop.

Generally, the utilization factors of the radial feeders for forming nominally closed loops must be less than 50% in normal operation to have enough ampacities in any abnormal situation. In other words, the cable size of a closed loop must have adequate capacity to carry all loads connected to it.

On the contrary, the VD feeders usually have long lengths and lower load densities. To ensure voltage drop at the end of a feeder is acceptable, their loadings are usually much lower than their capacities. The overhead feeders of Taipower distribution networks serving rural areas usually over 10 km in length, are operated under relatively light loading conditions. The voltage drop should be acceptable in any situations before or after the tie breaker is closed, even under abnormal operation conditions. The most severe condition is the tripping of one feeder main circuit breaker (FCB) placed near the power transformer, especially on the heavier loading side and under heavy loading condition. In this situation, the closed loop temporarily operates as a long radial feeder. The voltage drop at the end of this temporary radial feeder should be acceptable.

2) Type II: The feeders F#2 and F#3 are fed by two different transformers that are located in the same distribution substation, as shown in Fig. 1. They provide an alternative for tying these two radial feeders together at their ends to form a closed loop to provide better service continuity, classified as type II in this paper. All the factors of Type I arrangement should be considered. In addition, the following factors need also to be considered:

- the capacities and impedances of the two correlative substation transformers;
- the loadings and load characteristics of the two correlative substation transformers.

Hence, the problem of forming a closed loop of type II is more complicated than that of type I.

3) Type III: The feeder pair, F#3 and F#4, fed by two different transformers that are located in different distribution substations, was tied together to form a normally closed loop, classified as Type III in this paper. The impact factors of this type arrangement are functions of the natures of related feeders, substation transformers as well as the two correlative distribution substations. Therefore, more factors should be considered, as follows:

- all the factors considered in Type II;
- the short-circuit capacities (S.C.C.) of the correlative substations;
- the voltage levels of the correlative substations.

4) Summary: The impacts on the system and customers are least when using Type I arrangement to upgrade the primary feeders from originally radial or open-loop to normally closed-loop arrangement. In other words, Type I is assessed to be the simple one among the three types of arrangement and is also a feasible one for upgrading existing radial and open-loop feeders to closed loop. The factors to be considered in Type II arrangements are more complex than that in Type I. Therefore, more effort should be put into the upgrading. Type III is the most complicated arrangement. A lot of effort should be put into this kind of upgrading and into operations as well.

TABLE II
FACTORS INVOLVED IN UPGRADING OF FEEDER ARRANGEMENT

Factors	Types		
	Type I	Type II	Type III
S.C.C. at the primary sides of distribution substations (Difference in S.C.C.s)	– (–)	⊗ (–)	✓(✓)
Voltage levels of the primary sides of distribution substations (Difference in voltages)	– (–)	⊗ (–)	✓(✓)
Capacities of the substation transformers (Difference in capacities)	⊗ (–)	✓(✓)	✓(✓)
Impedances of the substation transformers (Difference in impedance)	⊗ (–)	✓(✓)	✓(✓)
Loadings of the substation transformers (Difference in loadings)	⊗ (–)	✓(✓)	✓(✓)
Load characteristics of the substation transformers (Difference in load characteristics)	⊗ (–)	✓(✓)	✓(✓)
Sizes of the feeders (Difference in sizes)	✓(✓)	✓(✓)	✓(✓)
Lengths of the feeders (Difference in lengths)	✓(✓)	✓(✓)	✓(✓)
Loadings of the feeders (Difference in loadings)	✓(✓)	✓(✓)	✓(✓)
Load distributions of the feeders (Difference of load distributions)	✓(✓)	✓(✓)	✓(✓)
Load characteristics of the feeders (Difference in load characteristics)	✓(✓)	✓(✓)	✓(✓)
Assessment	O	⌖	❁

Notes :
✓ : must be considered ⊗: dependence – : no effect or negligible
O : simple ⌖ : more complicated ❁ : most complicated

Assuming the networks are well designed, for Type II and III arrangements, no customer will have service interrupted even when a power transformer is out of service. If more service reliability is required, these two types of arrangement can be adopted. The factors which must be considered when upgrading a system to normally closed loop are summarized in Table II.

In Table II, the notation "dependence" means the factors may or may not be considered, depending on system conditions. In the following sections, four distribution feeders were utilized as sample feeders to demonstrate the impacts of the factors considered here.

III. The Sample System

Fig. 2 shows a part of a one-line diagram of the sample system, in which two substations, Hulin and Woulung substations, three power transformers and three normally closed-loop feeder circuits with three types of arrangement are shown, in order to bring out clearly the normally closed-loop arrangements and emergency ties of these arrangements. Originally, each transformer serviced six radial primary feeders. Four of the feeders from two different substations were chosen to form the three types of normally closed-loop arrangements, by tying the ends of each pair of the feeders together, one pair at a time.

The feeder mains are 500 MCM underground cables with series impedance of $0.1075 + j0.1437$ ohm/km and shunt admittance of j0.000 205 mho/km. The dots along the feeders, as shown in Fig. 2, represent balanced three-phase loads lumped at

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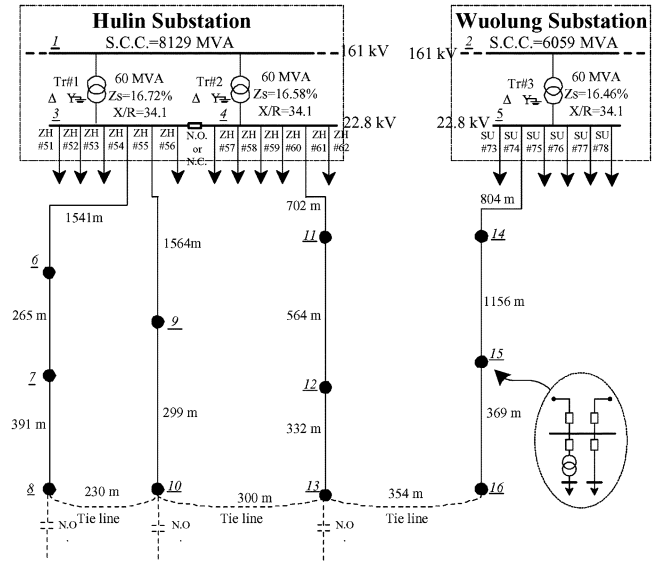

Fig. 2. One-line diagram of the sample system.

TABLE III
DEMANDS OF HIGH-VOLTAGE AND LOW-VOLTAGE CUSTOMERS

Bus Code	High Voltage Customers			Low Voltage Customers			
				Distribution Transformer			
	Equiv. load (kW+jkvar)	Motor Load	Static Load	Rating (kVA)	Impedance Z(%)	X/R	Equiv. Load (kW+jkvar)
6	2678+j880	44%	56%	500	4.5	5.5	380+j125
7	5206+j1710	58%	42%	1000	4.5	5.5	760+j250
8	3234+j1062	48%	52%	750	4.32	4.85	570+j187
9	1825+j1131	70%	30%	1333	4.5	5.3	906+j562
10	1352+j838	74%	26%	800	4.06	4.02	408+j253
11	1546+j508	47%	53%	666	4.5	4.7	505+j166
12	915+j300	54%	46%	300	3.5	2	228+j75
13	2928+j962	77%	23%	750	4	3.6	570+j187
14	1220+j756	79%	21%	500	4.5	5.5	340+j211
15	2485+j1540	80%	20%	1500	4.5	5.5	1020+j632
16	2127+j1319	60%	40%	833	4.5	5.2	566+j351

that location and fed by a distribution transformer. For simplification, the transformers and loads, shown in Fig. 2, are equivalents to represent large numbers of physical transformers and loads distributed along the feeders [9]–[11]. Table III gives the demands of high-voltage and low-voltage customers during the peak load period of a year. The low-voltage customers are fed by step-down distribution transformers. The other feeders, except the four sample feeders, are all simplified, represented as lumped-sum loads, as listed in Table IV. The loads were modeled as constant impedance in the power flow program of the ETAP PowerStation®.

For exploring the natures of different types of arrangements, three operating conditions are considered, as follows.

Condition A: Radial (Original or before-tie) condition, the ends of the feeder pair are open, therefore, the feeder pair is actually two radial feeders.

Condition B: Loop (After-tie) condition, the ends of the feeder pair are closed under normal operation, therefore, the feeder pair is tied together as a normally closed loop.

TABLE IV
LUMPED-SUM LOADS FOR THE OTHER FEEDERS

Feeder No.	Motor Load		Static Load	
	kW	kvar	kW	kvar
ZH#51	6726	2209	4678	1535
ZH#52	3268	1073	4332	1423
ZH#53	5301	1741	3249	1067
ZH#56	4323	1420	2327	764
ZH#57	2462	809	4378	1437
ZH#58	3720	1222	4735	1555
ZH#59	2309	758	5386	1769
ZH#60	2812	924	4218	1385
ZH#62	3192	1048	2128	699
SU#73	4807	1579	3933	1291
SU#75	4902	1610	3268	1073
SU#76	2964	973	4446	1461
SU#77	2138	702	2612	858
SU#78	3762	1236	4598	1510

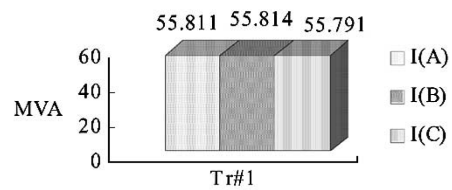

Fig. 3. The loading of substation transformer #1.

Condition C: Faulted condition, the normally closed-loop feeder circuit in condition B is sectionalized to two sections due to a feeder fault. The fault is assumed occurring at the feeding end of the heavy-loading side of the loop circuit. This is the most serious case of the feeder faults.

The power-flow and short-circuit analysis were performed to explore the natures of different types of normally closed-loop arrangements and determine the impacts to the system while upgrading to a normally closed loop.

IV. ANALYSIS AND DISCUSSION

The nature of three types of normally closed-loop arrangements under three operating conditions mentioned above are summarized here, based on the results of the power-flow and short-circuit analyzes. And, the advantages and disadvantages of the three types of arrangements are explored.

A. Type I

The feeder pair, ZH#54 and ZH#55, fed by the same power transformer, make up a normally closed loop of type I.

1) Transformer Loadings: The loading variations of the power transformer serving this feeder pair under three operating conditions are small, as shown in Fig. 3. The capacity of the power transformer need not be changed while upgrading radial feeders to normally closed loops of type I. It should be noted that in Figs. 3–6, the type of feeder arrangement is shown followed by the operation condition shown in a bracket. For example, ‘I(A)’ denotes that the data is for Type I arrangement under condition A.

2) Current Profiles: Fig. 4 illustrates the current profiles along the feeder pair. Generally, the current in each line segment will change when operating conditions change. The current

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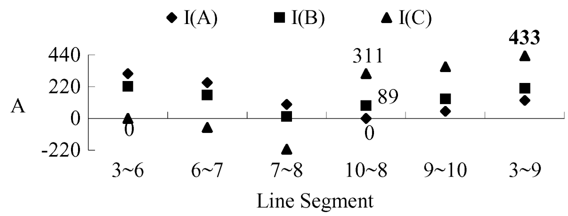

Fig. 4. Current profiles along feeders ZH#54 and ZH#55.

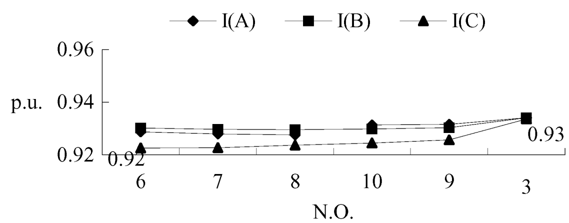

Fig. 5. Voltage profiles along feeders ZH#54 and ZH#55.

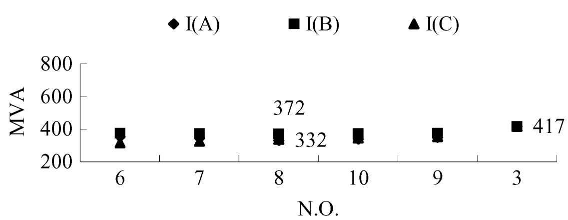

Fig. 6. The short-circuit capacities at buses along feeders ZH#54 and ZH#55.

in the line segments of the relatively heavier loading side of the loop will decrease while those on the lighter loading side increase. There is a current of 89 A flowing through the tie line from feeder ZH#55 to ZH#54. This fact results in the currents in each line segment along the feeder circuit becoming more uniform after the tie breaker is closed. That is, the operating condition is changed from A to B.

In condition C, assuming that the line segment 3–6 is isolated due to a fault occurring at that feeder segment, the loading will change dramatically and the directions of currents in some line segments may also change. For example, the current flow through bus 3–9 was increased to 433 A, this may overheat the feeder conductor.

3) Voltage Profiles: The average node voltages along the feeder circuit will be slightly increased. The voltages along the feeder ZH#54 were slightly increased while those along the feeder ZH#55 were slightly decreased, as shown in Fig. 5. Since the load diversity of the feeder pair is large, the variations of the line currents are therefore significant. Accordingly, the more load difference between the two feeders, the more line current and voltage variations rise.

4) Short-Circuit Capacities: The short-circuit capacities along the feeder circuit are shown in Fig. 6. The variations of the short-circuit capacities under three operating conditions are small. Generally, the farther the bus from the tie point, the less the increasing rate of short-circuit capacity obtains. For example, the short-circuit capacity of bus 8 was increased 12% when the two feeders were tied together as a closed loop.

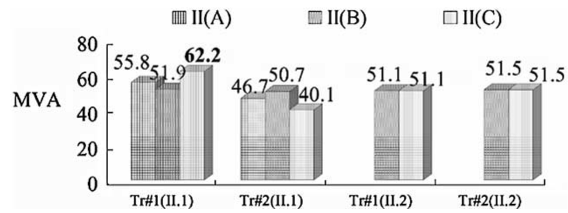

Fig. 7. The loadings of substation transformers #1 and #2.

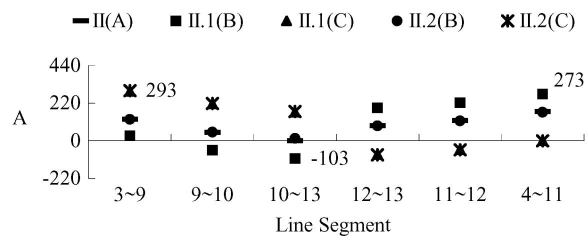

Fig. 8. Current profiles along feeders ZH#55 and ZH#61.

B. Type II

The feeder pair, ZH#55 and ZH#61, fed by two different power transformers that are located in the same substation, makes up a normally closed loop of type II.

1) Transformer Loadings: Fig. 7 shows the loading varieties of the correlative transformers. The loadings of Tr#1 and Tr#2 will become more balanced when the tie breaker is closed because the two correlative transformers share not only the loads of the feeder pair but also the loads connected to these two correlative transformers. The redistribution of the complex power of Tr#1 and Tr#2 caused Tr#2, with relatively lighter loading, to deliver extra complex power through feeders ZH#61 and ZH#55 to the loads on the secondary side of Tr#1, with relatively heavier loading. This fact results in the loading of Tr#1 decreasing and Tr#2 increasing.

In addition, while the line segment 4–11 was isolated due to a feeder fault, Tr#1 serves all the loads of the feeder pair of Type II.1 arrangement. However, for the Type II.2 arrangement the two power transformers will still share not only the loads of the feeder pair but also the loads connected to the secondary buses of the two transformers because the tie breaker is closed. Therefore, the loadings of these two transformers will not change much.

2) Current Profiles: Fig. 8 illustrates the variations of the currents in each line segment. For Type II.1 arrangement, the variations are significant. The directions of currents in some line segments of feeder ZH#55 were reversed. The current flowing in the tie line, between buses 13 and 10, is pretty high, 103 A. It is directly proportional to the loading difference of the two correlative transformers. Therefore, if the loading difference of these two transformers is large, the feeder pair may act as a transmission line to transfer mass power between the secondary buses of these two transformers. This may lead to the feeder pair being overloaded. This phenomenon should be avoided. Nevertheless, if more than one feeder pair between these two transformers are tied to form more closed loops, these loops will share the power need been transferred. Therefore, the impacts will be lessened. For Type II.2 arrangement, the varieties of line currents have the

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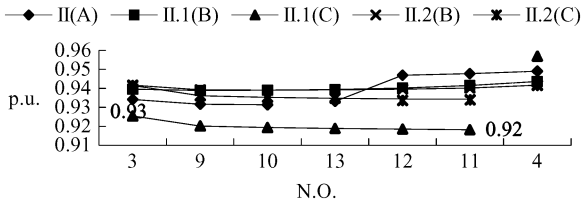

Fig. 9. Voltage profiles along feeders ZH#55 and ZH#61.

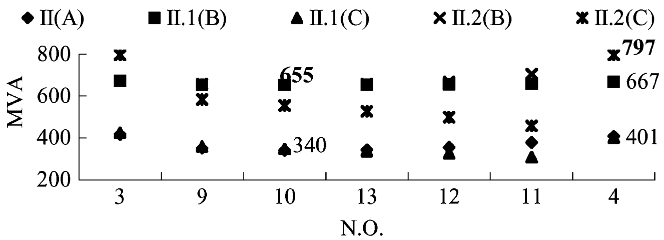

Fig. 10. The short-circuit capacities at buses along feeders ZH#55 and ZH#61.

same trends as those of Type I after the tie breaker was closed, as shown in Fig. 8.

3) Voltage Profiles: Fig. 9 depicts the voltage profiles of the nodes along the feeder pair. It is obvious that the node voltages along the feeder ZH#61 are descending while those along the feeder ZH#55 are ascending. This trend is similar to that of a Type I arrangement.

4) Short-Circuit Capacities: Fig. 10 shows the short-circuit capacities of nodes along feeders ZH#55 and ZH#61. The trends of variations of the short-circuit capacities are similar to those of Type I. When two radial feeders are tied, the short-circuit capacities of the buses along the feeders are almost doubled. However, the increasing rates of short-circuit capacities after the tie breaker being closed are much larger than those of Type I. The reason is that the fault current at each bus comes from two sources when the feeder pair is tied together. In addition, the varieties of the short-circuit capacities due to the line segment 4–11 being isolated are pretty different for Type II.1 and II.2, as shown in Fig. 10. Hence, upgrading the protective devices is usually required for both the distribution feeders and customers connected to them when upgrading the system type from radial to closed loop.

C. Type III

The feeder pair, ZH#61 and ZH#74, fed by two different power transformers located in different substations, makes up a normally closed loop of type III.

1) Transformer Loadings: Fig. 11 shows the loading variations of the two correlative transformers, Tr#2 and Tr#3 under specific system conditions. For Type III arrangement, the transformer loadings may total differently in different cases because they are sensitive to system conditions, such as the loading difference between two correlative transformers, the voltage difference between two correlative substations, and the difference in the short-circuit capacities between those two correlative substations. For example, if the voltage levels of the primary sides of the two correlative distribution substations are the same, the transformer loading variations are usually insignificant, if the difference of the loads connected to these two correlative transformers are not enormous. However, if the voltage levels of the primary sides of the two correlative distribution substations are different, for example, one is 161 kV and another one is 69 kV, then the transformer loading may vary significantly even if the difference of the loads connected to the two correlative transformers is not great. In this case, it is possible that mass power may flow from one transformer to the secondary bus or even back feed to the primary side of the other transformer, through the feeders that are tied at their ends normally. This condition is definitely undesirable.

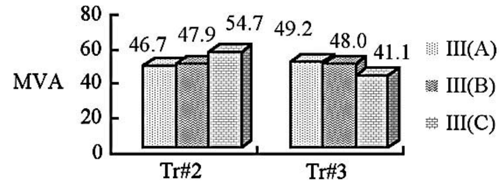

Fig. 11. The loadings of substation transformers #2 and #3.

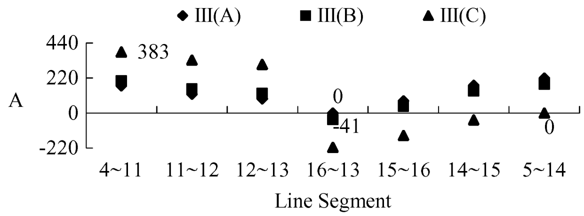

Fig. 12. Current profiles along feeders ZH#61 and SU#74.

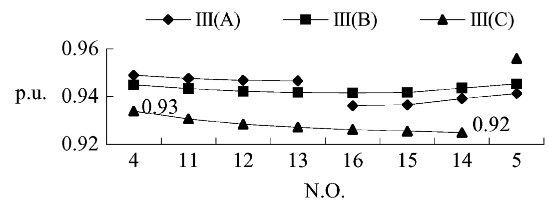

Fig. 13. Voltage profiles along feeders ZH#61 and SU#74.

In addition, the loadings and the differences of loadings of correlative transformers and feeders will also govern the variations of correlative transformer loadings. In other words, the variations of transformer loading are directly proportional to the factors just mentioned above. Consequently, if the primary sides of the correlative distribution substations are at the same voltage level, and the feeder loads and transformer loads are well balanced, then, the variations of transformer loading will be minor. The given conditions for Type III are the same as for the other two types in this paper, so the loading variations are similar to those of Type II.1, but are more sensitive to the loading differences of the two correlative transformers and voltage differences of the secondary buses of these two transformers.

2) Current Profiles: Fig. 12 illustrates the variations of currents flowing in each line segment under specific system conditions. Similarly, the current variations may total differently in other cases. The reasons are the same as those for the transformer loads. In the given conditions, the currents flowing in the feeder ZH#61 were increased after the tie breaker was closed, and the current flowing in the tie line, line segment 13–16, was 41 A.

3) Voltage Profiles: Fig. 13 depicts the voltage profiles along the feeder under specific system conditions. Similarly,

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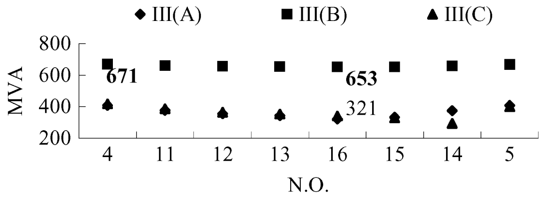

Fig. 14. The short-circuit capacities at buses along feeders ZH#61 and SU#74.

the voltage variations may total differently in other cases. The reasons are the same as those for the transformer loads.

4) Short-Circuit Capacities: Fig. 14 shows the variations of the short-circuit capacities. In the given conditions, they are similar to those of Type II. However, they may have totally different values in other cases because they are very sensitive to system conditions, especially the difference in short-circuit capacities of the two substations, and the variations of the short-circuit capacities are proportional to their difference. In the given conditions, the short-circuit capacity of bus 16 was increased 103%. The variations of the short-circuit capacities of the Type III arrangement are usually much larger than those of Types I and II. We should pay attention to this fact, because the large increment of the short-circuit capacities will result in the interruption capacities of the existing protection devices becoming inadequate. Two supporting measures may be used to alleviate this potential problem. The first is to insert two suitable current-limiting reactors at the feeding ends of the feeder mains, and the second is to upgrade the overcurrent protection devices of the feeders and of the customers along the feeders.

D. Discussion

Based on the simulation results, the impacts on the distribution systems and customers due to the upgrading of system type can be drawn, as shown in Table V. The impacts of Type I are the least among the three types of feeder arrangements. Hence, the type I arrangement is the easiest to use while upgrading a existing radial or open-loop system. This type has been used by Taipower to upgrade an existing radial system to a normally closed-loop system in metropolitan Taipei.

V. Required Supporting Measures

Once the system type is upgraded from radial or open-loop to a normally closed-loop arrangement, the existing software and hardware of the distribution system should be improved to meet the requirement of the new system with new feeder arrangement. Some major equipment may need to be replaced or adjusted to fit the changing of the system configuration and to ensure that the new system can operate successfully and get the expected benefit. The required supporting measures for the three types of feeder arrangements are listed in Table VI.

To achieve the main objective of no customer having interrupted service when a single fault occurs at the primary feeder, all the LBSs in the main loop circuit should be replaced by CBs with adequate interrupting capacity and required proper communication facilities. Coordination between the protection devices during normal and abnormal periods is definitely very important. The protection scheme of the normally closed loop is quite different from and also much more complicated than the conventional radial feeder. Therefore, the protection relaying system of the normally closed loop is usually capable of adaptive setting.

As mentioned before, the protection scheme of the normally closed loop is quite different from radial and open-loop feeder schemes. The latter two types of feeder are usually protected by traditional over-current relay. However, for the proposed normally closed loop, a pilot relaying system with the permissive

TABLE V
IMPACTS ON THE ORIGINAL SYSTEMS AND CUSTOMERS

Impacts	Types		
	Type I	Type II	Type III
Power flow	↓ (⇑)	↓ ~ ⬆$^+$ (⇑)	↓ ~ ⬆$^+$ (⇑)
Current flow	↓ (⇑)	↓ ~ ⬆$^+$ (⇑)	↓ ~ ⬆$^+$ (⇑)
Voltage drop	↓ (⇑)	↓ ~ ⇑$^+$ (⇑)	↓ ~ ⇑$^+$ (⇑)
Fault current and S.C.C.	↑ (↓)	⇑ (↓ ~ ⬆)	⇑ ~ ⬆$^+$ (↓)
Reliability and Service continuity	⇑	⇑$^+$	⬆$^+$
Capacities of the substation transformers	☺	😐	😐
Size of the feeder main conductors	☺	😐	😐
Switchgears and protection devices in the loop circuits	😐	😐	☹
Switchgears and protection devices of the customers	☺	☹	☹
Total impact	☺	😐	☹

Notation:
↑: increasing slightly ↓: decreasing slightly
⇑: increasing moderately ⇓: decreasing moderately
⬆: increasing significantly ⬇: decreasing significantly
( ): variations under abnormal condition (Condition C).
$^+$: highly depends on the system condition, case by case
☺ : slight 😐 : moderate ☹: significant

TABLE VI
REQUIRED SUPPORTING MEASURES OF SYSTEM UPGRADING

Items	Required Supporting Measures
Feeder main	• Types I and II.2: the feeder conductor must have adequate ampacity to carry all the loads connected to the loop circuit. • Types II.1 and III: the feeder conductor must have adequate ampacity to carry all the loads connected to the loop circuit and extra load transfer through the loop circuit from the secondary busbar of one transformer to the loads of the other transformer as well.
Substation Transformers	• Type II.2: The circulating current due to the parallel operation of the substation transformers must be overcome. • Types II.1 and III: The substation transformers must have enough reserved capacity to carry the extra loads under a condition of one substation transformer out of service.
Switchgears and Protection Devices	• Type I, II and III: All the LBSs in the main loop circuit should be replaced by circuit breakers with adequate interrupting capacity. The coordination between the protection devices is very important. More attention should be paid to the Type II and III arrangements to avoid the current backfeeding from the secondary side of substation transformers to the primary side. A simple distribution automation system may be built to better the system operation and maintenance.

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overreaching transfer trip (POTT) system and the directional comparison blocking (DCB) system were used. Moreover, intelligent electronic devices (IEDs) with Mirrored Bits fiber-optical channels and the functions of programmable logical controllers were used for the protection of the new system. Furthermore, all the LBSs were replaced by CBs to cooperate with the feeder automation system to ensure that the major goal of this pilot system could be achieved. This is the first time that a Taipower distribution system has adopted this kind of protection scheme. The significant changes in the protection systems required to get the improved reliability benefit will be addressed in other papers in the near future.

VI. Conclusion

In this paper, the impacts of upgrading existing primary feeders from radial to normally closed-loop arrangement were assessed. First, the factors that may affect the system upgrading were discussed. Next, a practical distribution system, that is also the first primary normally closed-loop system in Taiwan, was utilized as a sample system to reach some conclusions. From our results, Type I is the most simple and feasible arrangement to upgrade a existing radial or open-loop feeder system to a normally closed-loop system to eliminate customer interruptions due to a single fault at the feeder main. Finally, the required supporting measures of the system upgrading were noted. Based on the outcomes of this paper, three normally closed-loops have been created in the Taipei metropolitan area. The power quality, especially service reliability, has been improved considerably. In addition, the maintenance efforts have also been reduced dramatically.

After a thorough study, it was found that the type I arrangement meets all the requirements, such as a great improvement on the reliability, less impacts on the networks and customers, and easy to operate the new systems. Even though the reliability of Type III and Type II are greater than that of Type I, the Type I arrangement is considered as the most suitable and feasible one. Consequently, Type I was recommended to Taipower, and was also undertaken by Taipower to create three closed-loop feeders in the service area of Hulin Substation, Sinyi District, Taipei City. Many critical customers, such as Taipei World Trade Center Exhibition Hall, Taipei City Hall, Taipei City Council Hall, Hyatt Hotel, and many shopping centers are all located in this area. The closed-loop feeders were therefore considered suitable to serve this area. Three Type I closed-loop feeders have been created by Taipower in Taipei metropolitan area about one year ago. Taipower's field experience has totally supported the study results of this paper. A feeder fault has be experienced that make exactly only the CBs at each end of the faulted feeder segment been tripped and no customers were outage as expected.

Actually, the Type II arrangement was recommended to Taipower for forming a total new distribution network. In that case, the impacts on the customers can be avoided and better reliability can be obtained. This kind of arrangement is suitable for new science-based industrial parks and some specific districts where higher service quality is required. As for Type III, there are numerous factors which need to be considered and cost a lot, so Type III was not seriously considered for present use.

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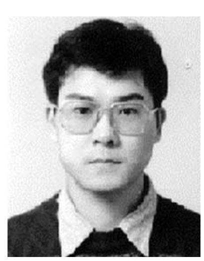

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