

Modified Techniques for Distribution System Reliability Improvement by Parallel Operation of Transformers

Ohn Zin Lin, Okka, Cho Cho Myint

Abstract—It is important to consider the effects of transformers on distribution system because they have the highest impact on system reliability. It is generally said that parallel operation of transformers (POT) can improve the system reliability. However, the estimation approach can be also considered for accuracy. In this paper, we propose a three-state components model and equations to determine the reliability improvement by POT, and cooperation of POT and distributed generation (DG). Based on the proposed model and techniques, the effect of POT is analyzed in four different tests with the consideration of conventional distribution system, distribution automation system (DAS) and DG. According to the results, the reliability is greatly improved by cooperation of POT, DAS and DG. The proposed model and methods are applicable to not only developing countries which have conventional distribution system but also developed countries in which DAS has already installed.

Keywords—Distribution system, reliability, dispersed generator, energy not supply, transformer parallel operation.

I. INTRODUCTION

DISTRIBUTION system reliability is critical issue in power system reliability. Therefore, many researches have been conducted to improve distribution system reliability (DSR) in [2], [8], [9]. DSR can be improved in many ways such as by considering protection system, installing DG, using automation system and so on. da Silva et al. stated the effect of prospered protection system, allocation of sectionalizing switches and control of protection devices on DSR in 2004 [2]. Then, researchers noticed the failure of protection system. Reliability evaluation including the failure of protection system was analyzed by Jiang et al. [3].

To improve DSR, dispersed generators (wind and solar) are introduced in [4]-[6]. Abdullah proposed a new method for assessment of dispersed generator which affects distribution system [7]. Generally, researchers investigate the effect of DG on radial system in previous researches. The evaluating of future power DSR including DG is researched in [8]. The reliability benefits of DG as a backup source are also presented in [9], [17].

Even though conventional protection devices can make system reliability better, the switching and isolation time take too long. Therefore, researchers propose the reliability

improvement by telecontrol of distribution switching devices. Since it allows to isolate the faulted sections and to restore the substantial ones as quickly as possible, the reliability is better [10]. The effect of distribution system automation on reliability is proved in [11]. Moreover, the impact of serve conditions caused by weather and the consequential impact of installing tie line are also already studied [12], [13].

As far as authors know, none of the previous works have investigated the different working process of parallel transformer operation after isolation. It is generally known that POT could make system reliability better. In fact, the model and evaluation techniques in [14] are not adequate as the different conditions of POT are not considered. If we use the conventional model, the estimations of reliability factors are not accurate. In this paper, we modify the three state model for POT and present an algorithm to calculate ENS (Energy Not Supply). According to the previous works [6], the failure of all components is considered together. However, the failure of transformers and the failure of section feeders are separately considered in this paper.

Using the modified methods, the effect of POT is analyzed in the different test systems with four different conditions. In the first test system, conventional protection devices are equipped. In the second, the system has conventional protection devices and DG. The third one equips DAS. The last one is the system with DAS and DG.

Reliability Index estimation using the model proposed in this paper is appropriated for POT because the switching, repairing and running conditions of every transformer respective to their deliverable capacity and loads are considered in details. If the amount of energy which cannot supply to the system is decreased, the system reliability becomes better. And it is important to estimate the amount of ENS in future. After that, we have to make some improvement to reduce ENS based on the estimation result. The more we can focus precisely the amount ENS, the more effective we can get for system.

II. TRANSFORMER PARALLEL OPERATION

To operate two or more transformers in parallel operation, it is necessary to connect the transformers to the same supply bus bars on both sides. In power system, such kind of requirement is frequently experienced in practice. The reasons for why parallel operation is necessary are as follows [15].

1. A single large transformer has not enough capacity to meet the total load demand.

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2. The power demand is increasing over a time with high capacity. Connecting transformer in parallel becomes popular in practice.
3. It is used to improve the system reliability. Although one of the transformers fails or is suspended for maintenance or repair, the load can continue in service.
4. It can also reduce the spare capacity. Many small rating transformers are used; one of those transformers can be used as a spare. If only one large transformer is feeding the load, a spare of similar rating one has to be available. Considering fewer transformers in service at a location, the problem of spares becomes more serious.
5. If there are any transportation problems to install large transformers, it may be easier to transport smaller ones to site and work them in parallel.

Fig. 1 shows the physical arrangement of two single phase transformers working in parallel on the primary side [15].

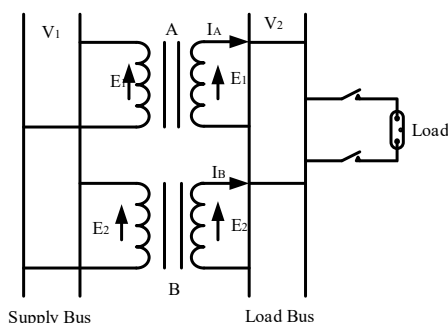


Fig. 1 Parallel operation of two single phase transformers

For connecting two or more transformers in parallel, it is necessary to consider certain conditions previously [15]. They are,

1. The voltage ratio must be the same.
2. Per unit impedance should be the same for each transformer.
3. To avoid circulating current between transformers, it is required to use the same polarity.
4. To avoid phase different problem, the phase sequence should be the same.

Factors in choosing transformer paralleling methods are proposed in [16].

III. EVALUATION TECHNIQUES

To evaluate the reliability, system average interruption frequency index (SAIFI), system average interruption duration index (SAIDI), customer average interruption duration index (CAIDI), and ENS index are used.

$$ENS = \sum L_{a(i)} U_i \text{ MWh/yr} \quad (1)$$

The $L_{a(i)}$ is defined as average load demand at load point "i" and U_i is outage time at load point "i". Reliability indices are applied to determine a customer's expectation such as interruption frequencies and durations [14].

According to the previous works described in [14], two-state component model is considered in general. Only repair and failure processes are considered as shown in Fig. 2 [14]. In some cases, breakers are not required to operate, e.g. open circuits and inadvertent operations of breakers. For these cases, two-state component model can be used. The model is:

1. State before the fault
2. State after the fault but before repair is completed.

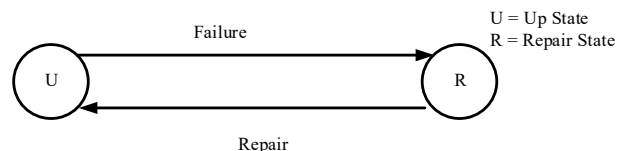


Fig. 2 Two-state component model

If switching actions occurs, a three-state model is required as follows:

1. State before the fault
2. State after the fault but before isolation
3. State after isolation but before repair is completed

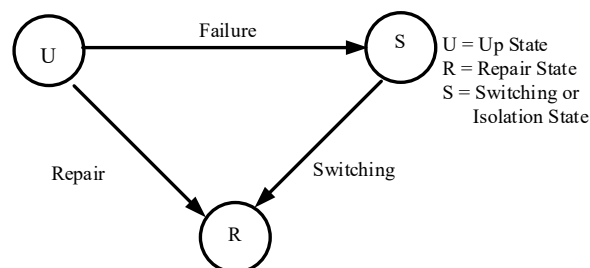


Fig. 3 Three-state component model

IV. MODIFIED MODEL AND EQUATION FOR POT

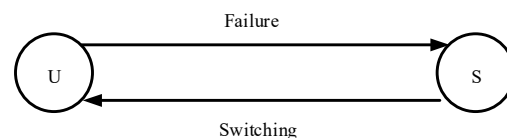


Fig. 4 Two-state component model for un-failure transformer

In transformer parallel operation, failed transformer and good transformer have different process. When a transformer is failure, other transformers will also be interrupted before isolation of failure one. Therefore, two different models are necessary. For the failure transformer, the model is the same as Fig. 3. On the other hand, for the other good ones, it is not necessary to repair. Only two-state component is required for good ones as follows (Fig. 4).

1. State before the fault
2. State after the fault but before isolation is completed.

Therefore, a model for transformer parallel operation can be modified as follows and shown in Fig. 5:

1. State before the fault
2. State after the fault but before isolation
3. State after isolation but:
 - a. before repair is completed

b. repair is not necessary and in good condition.

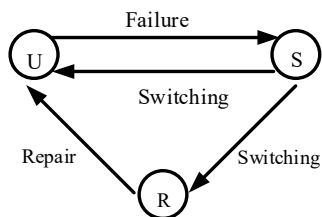


Fig. 5 Modified three-state component model for transformer parallel operation

To calculate the amount of ENS, both conditions of isolation and replacing/repairing/maintenance of transformers are necessary to consider separately. During the isolation period, all transformers will be interrupted. After isolation period, only failure transformer is interrupted for repairing, replacing or maintenance. Fig. 6 shows the sample operation of two parallel transformers.

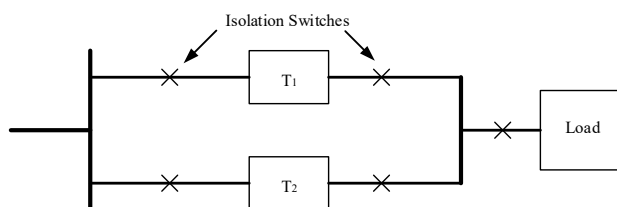


Fig. 6 Parallel operation of two transformers

$$ENS_{Tran} = ENS_S + ENS_R \quad (2)$$

where, ENS_{Tran} is ENS due to transformer, ENS_S is ENS during switching or isolation, and ENS_R is ENS during repairing, replacing or maintenance period of failure transformer.

During the switching time, total load is interrupted. Therefore, total load L_T and total outage time of two transformers U_S at load point caused by switching are necessary to consider as in (3).

$$ENS_S = L_T \times U_S \quad (3)$$

After isolation, the system will be supplied from the unfaulted transformer, but it may not supply the total load up to its capacity. It is necessary to consider the deliverable capacity of the substantial transformer to focus how many amount of energy can be supplied to the load.

$$ENS_R = (L_T - T_D) \times U_R \quad (4)$$

where T_D is deliverable capacity of the substantial transformer and U_R is the outage time caused by failure transformer. It is up to repairing, replacing or maintenance.

The deliverable capacity of transformer, T_D can be calculated simply by multiplying transformer rating and power factor. We have:

$$T_D = T_{rating} \times pf \quad (5)$$

By substituting the necessary equations, the ENS due to transformer parallel operation can be calculated as in (6). We assume that two transformers cannot be failure at the same time.

$$ENS_{Tran} = (L_T \times U_S) + [L_T - T_D] U_R \quad (6)$$

If the delivery capacity of running transformer is greater than or equal to the load, only interruption during isolation needs to be considered. Therefore, (7) can be used for this condition

$$ENS_{Tran} = L_T \times U_S \quad (7)$$

If DG is connected to the system, it will supply to the customers after the isolation of the failure transformer. For coordination with transformer operation in parallel and DG, the installed DG should be considered. The equation is modified as (8):

$$ENS_{Tran} = (L_T \times U_S) + [L_T - T_D - DG] U_R \quad (8)$$

If the amount of supply capacity from running transformer and installed DG is greater than the total load, $[L_T - T_D - DG] U_R$ become negative values. Therefore, it is not necessary to consider and (7) can be used for this condition.

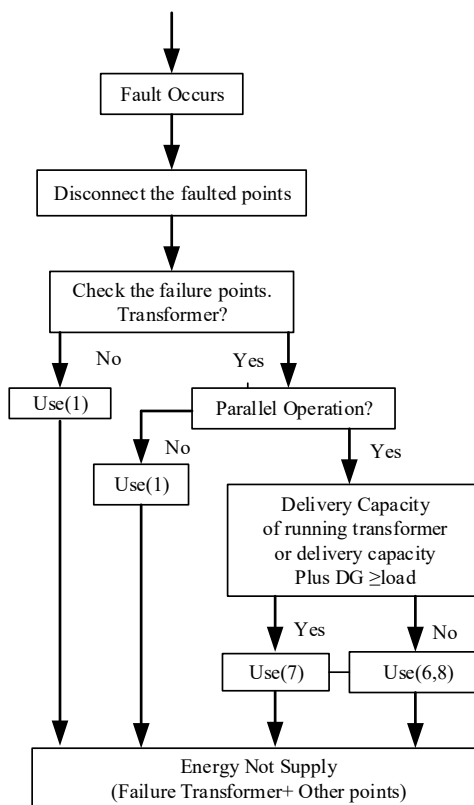


Fig. 7 Flow Chart of POT to Find the ENS

Fig. 7 shows the flow chart for POT. If a fault occurs, the faulted point will be disconnected and check the failure points. The failure of transformers and the failure of section feeders are considered separately. If the section feeders are failure, (1) is used. If transformers are failure, (6) and (8) are used. If the system has DG, (8) is used. Otherwise, (6) is used. Total ENS is obtained by summing up ENS caused by transformers and ENS caused by other point.

V. TEST SYSTEM

The test system used in this paper is Roy Billiton Test System of IEEE, RBTS Bus 2 as shown in Fig. 8 [1]. The system is connected for 20 MW load. The radial configuration is considered in [18].

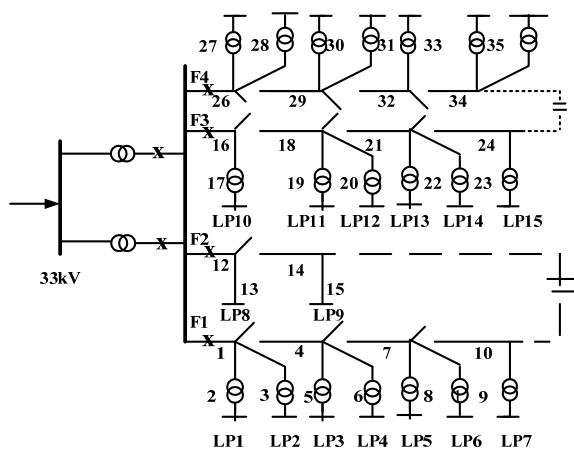


Fig. 8 Test system of RBTS Bus 2

The test system has four feeders and 36 feeder sections. Feeder types and lengths are listed in Table I with their section numbers. For calculation of indices, the failure of breaker and bus bar can be neglected because the failure ration is so small. The tie line effect is also neglected. The loading data for each customer and feeder are mentioned in Table II.

TABLE I
FEEDER TYPES AND LENGTHS

Feeder Type	Length (km)	Feeder section numbers
1	0.6	2,6,10,14,17,21,28,30,34
2	0.75	1,4,7,9,12,16,19,22,24,27,29,32,35
3	0.8	3,5,8,11,13,15,18,20,23,26,31,33,36

TABLE II
LOADING DATA

Feeder	Average Load (MW)	Peak Load (MW)	Numbers of customers
1	3.645	5.934	652
2	2.15	3.5	2
3	3.106	5.057	632
4	3.39	5.509	622
Total	12.291	20	1908

Reliability and system data are shown in Table III. The λ is failure rate per year per kilometer for lines and, failure rate per

year for transformers. Constant r is repair time in hour. Constant r_p is replacement time by a spare in hour.

TABLE III
RELIABILITY AND SYSTEM DATA

Component	λ	r	r_p	s
33/11 Transformer	0.015	200	15	1
11/0.4 Transformer	0.015	200	10	1
11kv Lines	0.065	5		1

Constant s is switching time in hour. The fuse gear and disconnects in the radial feeders are assumed to be 100% reliable. Assume that 11 kV source breaker operates successfully when required, disconnects are open whenever possible to isolate a fault.

TABLE IV
TRANSFORMER RATING FOR EACH LOAD POINT

Load Points	Average Load (MW)	Peak Load (MW)	Single (MVA)	Parallel (MVA)
1-3, 10,11	0.535	0.8666	1	0.5
12, 17-19	0.450	0.7291	1	0.5
4,5,13,14,20,21	0.556	0.9167	1.5	7.5
6,7,15,16,22	0.454	0.7500	1	0.5

The rating of 33/11 kV transformer is 16 MVA each. The installed transformers rating is necessary to assume according to their connected loads. Assume that power factor is 0.9. In Table IV, the minimum required capacities are suggested. If more capacity is installed, the reliability is better.

VI. TEST RESULTS

In this paper, effect of parallel transformer operation is analyzed with four tests as follows:

1. The system with conventional protection devices and without DG.
2. The system with conventional protection devices and DG is connected to the loads.
3. The system with DAS and without DG.
4. The system with DAS and DG.

For above four tests, four difference cases were considered:

- a. Case 1: Transformers are repaired
- b. Case 2: Transformers are replaced
- c. Case 3: Transformers are operated in parallel and the failure ones are repaired
- d. Case 4: Transformers are operated in parallel and the failure ones are replaced.

For case 1 and 2, single 32 MVA is considered for 33/11 kV transformer. The rating of single transformer listed in Table IV is considered for 11/0.4 kV transformer. In case 3 and 4, 16 MVA for 33/11 kV and the rating listed in Table IV are considered for 33/11 and 11/0.4 transformers.

The failure rate of feeder section is 0.065 f/yr-km. Therefore, it is necessary for the failure of each feeder section to be calculated according to their lengths. In Table V, reliability data of feeder sections are calculated.

Using the test system data and evaluation techniques, the reliability indices for each case can be calculated simply by using excel sheet. Detailed calculation methods can be seen in

[14]. Average load and peak load are denoted as load level 1 and 2. The effect of POT and coordination with DG differs according to the load level. Therefore, two different load levels are considered in this paper.

TABLE V
RELIABILITY DATA OF FEEDER SECTIONS

Feeder section numbers	Length (km)	Failure rate (f/yr)
2,6,10,14,17,21,28,30,34	0.6	0.0390
1,4,7,9,12,16,19,22,24,27,29,32,35	0.75	0.0488
3,5,8,11,13,15,18,20,23,26,31,33,36	0.8	0.0520

A. System with Conventional Protection Devices and Without DG

Fuses and disconnecting switches are used for protection in the test system, but without DG. According to the results from different cases, POT can reduce the switching time and interruption time. Consequently, the system reliability is better.

TABLE VI
EFFECT OF TRANSFORMER WITHOUT DG FOR LOAD LEVEL I

Failure Component	ENS (MWh/yr) affected by Failure Component			
	Case 1	Case 2	Case 3	Case 4
Feeder Sections	10.0926	10.0926	10.0926	10.0926
11/0.4 kV Transformers	30.4230	1.5211	1.4871	0.2189
33/11 kV Transformer	36.8730	2.7655	0.1844	0.1844
Total ENS	77.3886	14.3792	11.764	10.4958

Table VI shows the effect of replacing and POT for load level 1. In cases 1 and 2, the ENS caused by 11/0.4 kV decreases from 30.423 MW to 1.5211 MW by replacing failure transformer instead of repairing. By comparing case 1 and 3, the effect of parallel operation can be seen clearly. Even though the spare transformer is not available for replacement, the system reliability is improved highly by POT. Case 4 is the same as case 2 which shows the effect of transformer replacing.

In test system, though one of the 33/11 kV transformers (16 MVA) is failure, the capacity of the other one is 14.4 MW which is greater than the load level 1. Therefore, the system will be interrupted only during the switching of failure transformer. ENS in cases 3 and 4 are the same because the system is interrupted only in switching time whether the failure one is repaired or replaced. However, they will not be same if the load become greater than the deliverable capacity of transformer.

Table VII shows the effects of transformer for load level 2. The amount of ENS is surely increased as load level is increased. The POT could decrease the amount of ENS. In case 3, as the deliverable capacity is less than the load, some of loads are interrupted while the failure transformer is repairing, and the ENS is significantly large. For higher load condition, more transformer should be installed in parallel or spare ones should be available as in case 4.

The effect of transformer replacing can be checked by comparing cases 1 and 2, and also cases 3 and 4. The effect of transformer's parallel operation can be analyzed by comparing

with case 1 to case 2 and case 3 to case 4.

TABLE VII
EFFECT OF TRANSFORMER WITHOUT DG FOR LOAD LEVEL 2

Failure Component	ENS(MWh/yr) affected by Failure Component			
	Case 1	Case 2	Case 3	Case 4
Feeder Sections	16.4324	16.4324	16.4324	16.4324
11/0.4 kV Transformers	49.5018	2.4751	18.6993	0.3738
33/11 kV Transformer	60	4.5	17.1	1.56
Total ENS	125.754	23.2272	52.2317	18.3661

B. System with Conventional Protection Devices and DG

In this test, DG is installed on each tie line. The capacity of each DG is 2.5 MW. For this test, the effect of DG and the coordination effect of DGs and POT can be seen clearly.

TABLE VIII
EFFECT OF TRANSFORMER AND DG FOR LOAD LEVEL I

Failure Component	ENS (MWh/yr) affected by Failure Component			
	Case 1	Case 2	Case 3	Case 4
Feeder Sections	5.5511	5.5511	5.5511	5.5511
11/0.4 kV Transformers	30.3294	1.5211	1.4871	0.2189
33/11 kV Transformer	21.873	1.6405	0.1844	0.1844
Total ENS	57.7535	8.7128	7.2226	5.9544

According to the comparison of Table VI and VIII, the reliability is improved by DGs. ENS affected by 33/11 kV transformer is decreased in cases 1 and 2, and the same in cases 3 and 4 because the deliverable capacity of transformer is larger than the load. However, the total ENS decreases in all cases. ENS affected by 11/0.4 kV transformer does not decrease because DGs are installed in 11 kV feeders.

TABLE IX
EFFECT OF TRANSFORMER AND DG FOR LOAD LEVEL II

Failure Component	ENS (MWh/yr) affected by Failure Component			
	Case 1	Case 2	Case 3	Case 4
Feeder Sections	11.0978	11.0978	11.0978	11.0978
11/0.4 kV Transformers	49.4575	2.4751	18.6993	0.3738
33/11 kV Transformer	45	3.375	2.1	0.435
Total ENS	105.555	16.9479	31.8971	11.9066

In Table IX, the effect of transformer and DG for load level 2 is shown. ENS affected by 33/11 kV transformer failure decreases from 45 MWh/yr to 2.1 MWh/yr by POT if the failure transformer is repaired. If the failure one is replaced, ENS decreases from 3.375 to 0.435 MWh/yr.

By comparing Tables VII and IX, the reliability is improved by DG in all cases. In case 3, ENS decreases from 17.1 MWh/yr to 2.1 MWh/yr because of POT and DG. The effect of DG and POT is noticeable for higher loads.

C. System with DAS

In this test, the switching time of disconnecting switches is changed from 1 hr to 0.0167 hr and the repair time is changed from 5 hrs to 0.5 hr. The isolation time of failure transformer

is 0.05 hr.

TABLE X
EFFECT OF TRANSFORMER AND DAS FOR LOAD LEVEL I

Failure Component	ENS (MWh/yr) affected by Failure Component			
	Case 1	Case 2	Case 3	Case 4
Feeder Sections	0.9509	0.9509	0.9509	0.9509
11/0.4 kV Transformers	30.4123	1.5105	1.3426	0.0744
33/11 kV Transformer	36.873	2.7655	0.0092	0.0092
Total ENS	68.2362	5.2268	2.3027	1.0345

By using DAS, the ENS caused by feeder sections is decreased from 10.0926 MWh/yr to 0.9505 MWh/yr for load level 1 according to the results from Tables VI and X. The switching and isolations of failure transformers periods are also reduced. Therefore, ENS affected by transformers also decreases.

Table XI shows the effect of transformer and DAS for load level 2. ENS caused by feeder sections decreases from 16.4324 MWh/yr to 1.5488 MWh/yr if compared with Test A. In this test, when the load is changed to higher level, ENS caused by transformers increases as shown in case 3.

TABLE XI
EFFECT OF TRANSFORMER AND DAS FOR LOAD LEVEL II

Failure Component	ENS (MWh/yr) affected by Failure Component			
	Case 1	Case 2	Case 3	Case 4
Feeder Sections	1.5488	1.5488	1.5488	1.5488
11/0.4 kV Transformers	49.4841	2.4574	14.1136	0.7174
33/11 kV Transformer	60	4.5	16.815	1.275
Total ENS	111.033	8.506	32.4773	3.5412

D. System with DAS and DG

In this test, both DAS and DG are installed. The switching time and DG information are the same as previous sections.

TABLE XII
EFFECT OF TRANSFORMER, DAS AND DG FOR LOAD LEVEL I

Failure Component	ENS (MWh/yr) affected by Failure Component			
	Case 1	Case 2	Case 3	Case 4
Feeder Sections	0.3915	0.3915	0.3915	0.3915
11/0.4 kV Transformers	30.4332	1.5098	1.3426	0.0744
33/11 kV Transformer	21.873	1.6405	0.009	0.009
Total ENS	52.6978	3.5418	1.7433	0.4751

TABLE XIII
EFFECT OF TRANSFORMER, DAS AND DG FOR LOAD LEVEL II

Failure Component	ENS (MWh/yr) affected by Failure Component			
	Case 1	Case 2	Case 3	Case 4
Feeder Sections	0.637	0.637	0.637	0.637
11/0.4 kV Transformers	49.5185	2.4568	14.1136	0.7174
33/11 kV Transformer	45	3.375	11.265	0.8588
Total ENS	95.1555	6.4688	26.0156	2.2132

According to Table XII, ENS affected by both feeder sections and transformers decreases significantly. Reliability is

the best in this test and total ENS is only 0.4751 MWh/yr for case 4.

According to Table XIII, we can see that the reliability level is improved if compared with other tests. Even for high load level 2, the total ENS is only 2.2132 MWh/yr in case 4. For both of load level 1 and load level 2, POT has better impact if the system is operated with DAS and DG.

Finally, the results are compared in four different tests as shown in Fig. 9. From the results, case 1 was the worst and case 4 is the best for reliability.

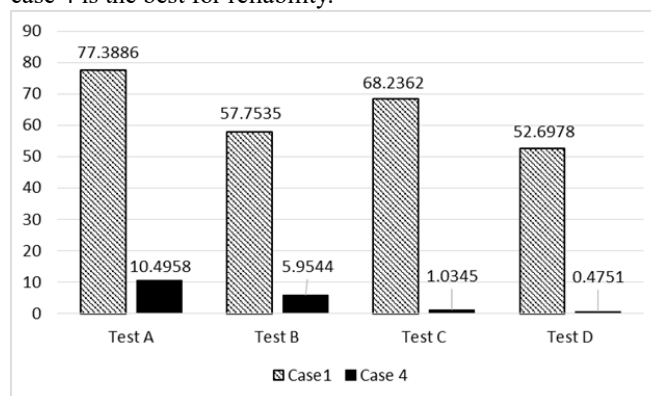


Fig. 9 Comparison of ENS for four tests

In case 1 of every test, most of ENS is due to 33/11 kV and 11/0.4 kV transformers. By POT and repairing of failure transformers as in case 4, the amount of ENS decreases greatly. By comparing Test A and Test B, ENS in case 1 decreases from 77.3886 MWh/yr to 57.7535 MWh/yr due to DG. In Test C, though DG is not installed, ENS is improved if compared with Test B. In Test D, ENS decreases again because of DG. By comparing Test A and Test C, ENS is reduced from 77.3866 MWh/yr to 68.2362 MWh/yr because of DAS. In Test D, when the system is with DAS and DG, ENS in case 4 is only 0.4751 MWh/yr. It is the best for system reliability in all tests.

VII. CONCLUSION

In this paper, the effect of transformer is analyzed in three cases, that is, repairing, replacing and parallel operating. We propose a modified model to calculate reliability index, ENS. Moreover, the effect of DG coordinated with transformer's parallel operation is also analyzed. Numerical experiments with modified equations are conducted in the RBTS bus 2 system.

According to the results, most of ENS is caused by transformer's failure. The POT has beneficial for both low and high load levels. Although the spare transformer is not available to replace the failure one, the system can get supply after isolation period. For extended load, installing one more transformer in parallel system is more economical and reliable. For increasing condition of load, the coordination of DG and POT is one of the solutions to reduce the amount of ENS.

In this paper, as DGs are installed in 11 kV lines, DGs cannot save the ENS caused by 11/0.4 kV transformers. In

future, we can consider DG's installation in 0.4 kV lines. Moreover, DAS decreases the isolation time of failure transformer and disconnecting time of faulted parts, and the system reliability becomes better and better. Therefore, the impact of POT, DG and DAS are important to take account in power system reliability. The proposed model and concepts are useful to analyze system reliability in all conditions for both under developing countries and developed countries.

ACKNOWLEDGMENT

This work was supported by Yangon Technological University and Ministry of Education.

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