Reliability Assessment of Distribution Stations Considering Spare Transformer Sharing

Gomaa A. Hamoud, *Senior Member, IEEE*

***Abstract*—A reliability study has been performed recently at Hydro One to evaluate the reliability of groups of distribution stations involved in a spare transformer sharing policy. The groups may include distribution utilities stations and distribution customer own stations. The study used a probabilistic method based on stationary Markov models and two performance criteria namely the group availability criterion and the total cost criterion in the evaluation. The study results demonstrate that the number of spare transformers required for the groups involved in the spare transformer sharing policy will be reduced while maintaining almost the same reliability levels of individual groups. The purpose of this paper is to describe the study, its reliability assessment method and to illustrate it using a sample system.**

***Index Terms*—Distribution stations, regular transformers, spare transformers, stationary Markov models, major transformer failures, group availability, total cost.**

I. Introduction

Distribution utilities may have different groups of similar power transformers and these power transformers can vary in ratings and voltage levels. Spare transformers are normally provided for the various groups to cover major failures (Class I failures) to their regular power transformers. When the sizes of some groups are small, it may be costly to provide spare transformers for each individual group. Therefore, distribution utilities may decide to share spare transformers with other utilities in order to reduce the cost of carrying them. Also, customers that own their distribution stations may form an alliance with one another or with distribution utilities to share spare transformers. The purpose of the alliance is to benefit its members in terms of reducing the cost of carrying the spare transformers.

Spare transformers have been used by distribution utilities for a long time to improve the reliability of supply to their customers. Probabilistic methods and models were introduced to determine the number of spare transformers required for a group of similar power transformers [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14]. These probabilistic methods used the binomial distribution, Poisson distribution, Markov models and Monte Carlo simulation techniques in determining, under different criteria, the required number of spare units.

At Hydro One, a number of spare reliability studies has been performed. In these studies, two performance criteria namely the group availability criterion and the system minimum total cost criterion were used in determining the required number of spare units. The first criterion assumes that a pre-determined level of group availability is given and the spare units are added to the population, one at a time, until the required level of group availability is reached. The second criterion is based on the minimization of the total system cost (cost of carrying spares and outage costs resulting from unit failures). The required number of spare units (optimal number) is determined when the total system cost is minimum. Reference [11] presented a probabilistic method based on Markov models for determining the number of spare transformers (regular units and mobile units) required for a group of similar distribution transformers. The method used the two mentioned performance criteria in determining the required number of spare units. The version of the Markov model that handled only the regular spare transformers is used in this paper. Reference [15] described a reliability model for estimating the number of spare parts required for a group of similar parts in order to meet a pre-determined level of the group availability. The model was based on a stationary Markov process and accounted for a number of factors that affect the number of spare parts such as the group size, bundle size, part failure rate, part replacement time, part installation rate and any redundancy in the bundles. A modified version of that model is used in this paper.

The subject of sharing spare transformers among different distribution utilities may be new. Sharing spare transformers will provide economic benefits to all utilities involved in the spare transformer sharing policy. It seems, after searching the available literature that no technical work on the subject has been reported. This paper may be first of its type in addressing the subject of sharing spare transformers in distribution stations. The sharing spare transformer policy could be between distribution utilities, distribution customers that own their stations or a combination of both.

A reliability study has been performed recently at Hydro One to evaluate the reliability of distribution stations involved in the spare transformer sharing policy. This paper describes the study and its findings.

The main contributions of the paper are:

- Presenting a probabilistic method for evaluating the reliability of distribution stations with spare transformer sharing.
- Illustrating the proposed assessment method using a sample from the Hydro One's distribution system.

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The author is with Hydro One Inc., Toronto, ON, Canada (e-mail: gomaa.hamoud@hydroone.com).

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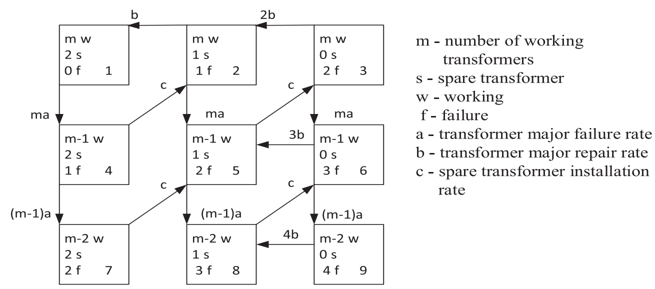

Fig. 1. Markov model for a group of m regular transformers with two spare transformers.

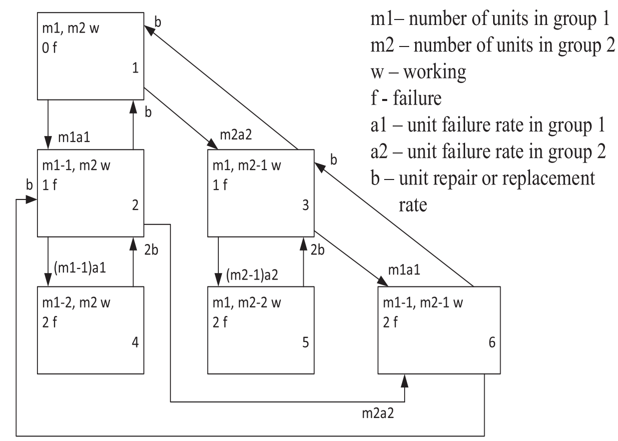

Fig. 2. Markov model for the combined group with different failure rates –no spare transformers.

II. Method of Reliability Evaluation

There are two performance criteria normally utilized in estimating the number of spare units for a group of similar distribution power transformers. The two criteria are the group availability criterion and the total cost criterion. The two criteria require the calculations of transformer failure probabilities. In addition, the total cost criterion requires the assessment of transformer failure consequences. In this study, both criteria are used in the spare assessment of the groups involved in spare transformer sharing. The number of groups can be two or more and each group can have one transformer or more.

It should be mentioned that the proposed reliability assessment method can also be applied to power transformers used in high voltage load stations (or customer delivery systems). A customer delivery system is part of the bulk transmission system and is defined as the component of the bulk transmission system which delivers power from the bulk transmission system to large municipalities, large industrial customers and the retail (distribution) system. A customer delivery system can have one transformer or more. On the other hand, the application of the proposed method to high voltage auto-transformer stations in bulk transmission systems is unlikely since it may be hard to combine the transmission network systems of the groups involved in the spare transformer sharing policy.

The following assumptions have been made in the study:

1) The number of transformers in each group can be small or large.
2) Each station in each group has only one transformer.
3) The loss of one transformer will constitute a group failure.
4) Transformers in various groups can have different major failure rates.
5) Spare transformers, if available, are installed first before any repairs or replacements to failed transformers.
6) Regular and spare transformers have the same failure rates.
7) There are no load transfers between stations in case of transformer failures.

It is worth mentioning that the proposed method of assessment can also be extended to handle changes in some of the above assumptions such as the number of transformers per station and load transfers between stations. In those cases, assessment methods similar to those presented in [13] and [14] can be developed to address the issues of redundancy and load transfers between the stations for each individual group. When the groups are combined, Markov models similar to those in Figs. 2-3 can be used in the assessment. The issues of redundancy and load transfers are beyond the scope of this paper.

For illustration purposes only, it is assumed that spare transformers are shared by two groups, Group 1 and Group 2. Two cases are assessed in this study: one assumes that all transformers in the two groups have the same failure rate and the other assumes that the transformers in the two groups have different failure rates. The two cases are now discussed in detail.

A. *Case 1: All Transformers Have the Same Failure Rate*

The Markov model introduced in [11] for analyzing Class I transformer failures of power transformers is used in this study. Fig. 1 shows a Markov model for a group of m regular transformers with two spare transformers. The main input parameters to the model are the group size (m), transformer major failure rate (a), spare transformer installation rate (c) and the transformer major repair rate (b). In addition to the installation time, the time required to move a spare transformer from a storage to a trouble station can also be included in the assessment. In this case, the installation rate will be equal to the reciprocal of the sum of the installation time and the transportation time. The repair rate used in the model is the reciprocal the time required either to repair a failed unit or to purchase a new unit. Therefore, the parameters, c and b can be chosen to suit the transformer group under consideration.

Referring to Fig. 1 and based on the group failure criterion, States 1, 2 and 3 are success states while the remaining states are failure states. The group availability for the system shown in Fig. 1 is equal to the sum of probabilities of States 1, 2 and 3.

In general, the group reliability indices such as the group availability index and the group unsupplied energy index depend on the number of spare transformers. A Markov model would be required for a given number of spare transformers and the associated Markov states can be classified into success and failure states.

The reliability evaluation process involves the following steps when the group availability criterion is utilized:

a) Apply the Markov model to Groups 1 and 2 to obtain the group availability as a function of the number of spare transformers for each group.

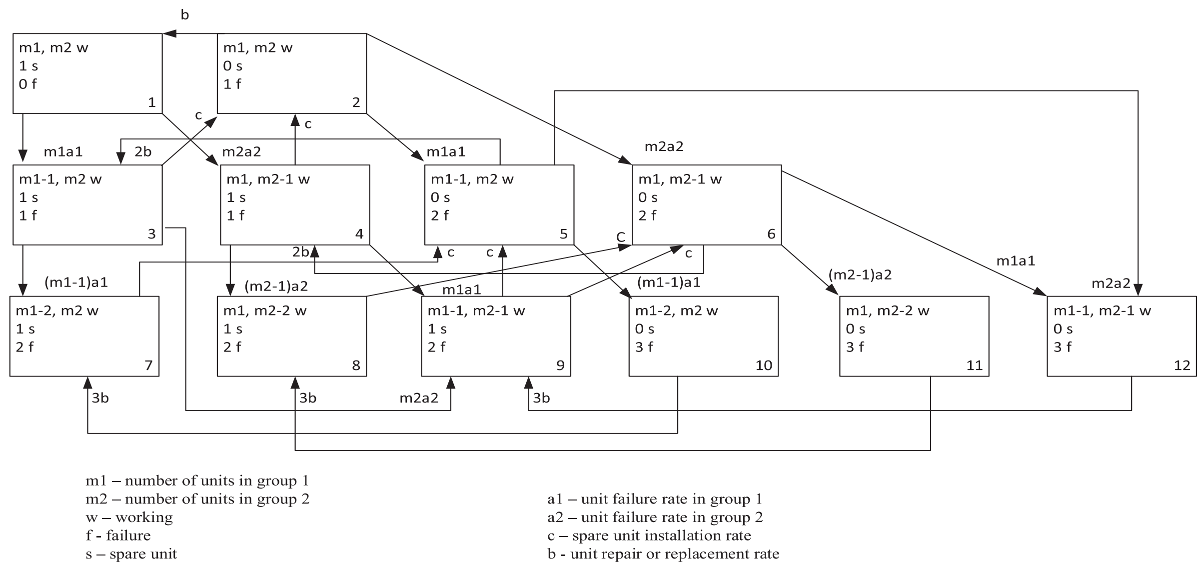

Fig. 3. Markov model for the combined group with two different failure rates – one spare transformer.

b) Apply the Markov model to the combined group (Groups 1 and 2) to obtain the group availability as a function of the number of spare transformers.
c) Select the group availability level to be utilized. A particular level can be chosen or the level when the group availability saturates can be used.
d) Use the results in Steps a and b and the selected level of the group availability in Step c to determine the required number of spare transformers for each group.

It should be mentioned that the number of spare transformers determined for the combined group must be less than the sum of spare transformers determined for both groups in order to support the spare transformer sharing policy.

B. Case 2: Transformers in the Two Groups Have Different Failure Rates

One may ask that can Markov models of [11] still be used when the failure rates of transformers in the two groups are different. The answer to this question is yes and, in this case, the unit failure rate to be used in the assessment should be the weighted average of the two group failure rates. The proof of the answer is provided as follows:

The required Markov models for the case can be modified versions of those described in [15] for the case with two groups of bundles with different bundle sizes. The only differences between the original Markov models and the modified ones are that the two groups of bundles have different failure rates and the size of each bundle is assumed to be one. Fig. 2 shows the modified Markov model for the combined group with no spare transformers. The group availability for the case with no spare transformers is equal to the probability of being in State 1.

Fig. 3 shows the modified Markov model for the combined group with one spare transformer. The group availability in this case is equal to the sum of probabilities of States 1 and 2. The number of Markov states increases by 6 each time a spare transformer is added to the group.

It should be mentioned that a modified Markov model will be required for a given number of spare transformers.

It was found and also as shown in the illustrating example that the modified versions of Markov models of [15] and those of [11] produce the same results when the weighted average unit failure rate of the transformers involved is used in Markov models of [11].

When the total cost criterion is used in the evaluation, the total cost includes the cost of carrying spare transformers and the failure cost resulting from transformer failures. The number of spare transformers required is determined when the total cost is minimum.

The evaluation process involves the following steps:

1) Estimate the capital cost of a spare transformer.
2) Select the outage level to be used in the Markov model (normally 2).
3) Add spare transformers to the group, one at a time, and use the associated Markov model to calculate for each case, the probabilities of various outage levels.
4) Calculate the annual interruption cost for cases without and with spare transformers using the following equation:

$$\mathrm{AIC} = \mathrm{POL_1 T\ TR\ CIC} + \mathrm{POL_2 T\ 2\ TR\ CIC} \quad \$/\mathrm{year} \tag{1}$$

where:

AIC	Annual interruption cost in dollars.
POL_1	Probability of outage level 1
POL_2	Probability of outage level 2
TR	Transformer rating in MW
CIC	Customer interruption cost in $ per MWh
T	Number of hours in a year (8760 hours assumed).

The first term on the right hand side of (1) represents the outage cost due to single transformer outages while the second term represents the outage cost due to double transformer outages.

5) Calculate, for each case, the annual cost of carrying spare transformers using the following formula:

$$\text{ACC} = \text{C X ADR} \quad \$/\text{year} \tag{2}$$

where:

ACC Annual carrying cost in dollars
X Number of spare transformers
C Cost of one spare transformer in dollars
ADR Annual discount rate in per unit.

6) Calculate, for each case, the annual total cost which is the sum of AIC and ACC.
7) Use the results in Step 6 to determine the optimal number of spare units (the number corresponding to the minimum annual total cost).

It should be mentioned that, for the purpose of illustration only, a simple method is used to calculate the annual carrying cost of spare transformers and is given by (2).

The costs considered in the total cost criterion include only the cost of spare transformers and the customer interruption cost. Other costs such the cost of maintaining and storing the spare units, the cost of transporting the spare units, etc. are normally much smaller than the capital cost and the outage cost and can also be included in the assessment. Each additional cost component should be expressed on a yearly basis and be added to the right hand side of (2).

The above assessment process should be applied to Group 1, Group 2 and the combined group.

The parameters POL1 and POL2 in (1) for the case with two spare transformers, see Fig. 1, are given by:

POL1 = Sum of probabilities of States 4, 5 and 6.
POL2 = Sum of probabilities of States 7, 8 and 9.

It should be mentioned that the proposed assessment method is general and can handle many groups with the same unit failure rate or different unit failure rates.

In addition, the issue of the cost sharing of spare transformers among the participating members was not addressed in this paper. The cost sharing scheme can be simple or complicated and may depend on a number of factors such as the size of each group, ages of its elements, its failure rate, condition of each element, etc. A simple and fair scheme may account for the size of each group and its failure rate. To illustrate, suppose that there are two groups of sizes n1 and n2 and their annual failure rates are $\lambda 1$ and $\lambda 2$. The cost of spare transformers may be split between the two groups as follows:

Group 1 share = n1 λ1/(n1 λ1 + n2 λ2)
Group 2 share = n2 λ2/(n1 λ1 + n2 λ2).

III. An Illustrating Example

Two small groups of distribution power transformers were used to illustrate the proposed method of assessment. Group 1 has 13 transformers and Group 2 has 7 transformers. The following data based on Hydro One's distribution system was used for the illustration purposes only:

TABLE I
GROUP AVAILABILITY–CASE WITH A LOW TRANSFORMER FAILURE RATE

Annual Transformer Failure Rate	Number of Spare Transformers	Group Availability	
		Markov Model of [11] (**)	Modified Markov Model of [15]
0.00372 for both groups	0	0.89484	0.89484
	1	0.98824	0.988254
	2	0.99403	0.994042
	3	0.99427	0.994278
0.00372 for Group 1 0.00744 for Group 2 (*)	0	0.86010	0.86105
	1	0.98157	0.98162
	2	0.99169	0.99171
	3	0.99225	0.99227

(*) – Transformer failure rate in Group 2 is twice that of Group 1.
(**) – A weighted average transformer failure rate of .005022 was used [(13x .00372+7 x 2 x .00372)/20 = .005022].

TABLE II
GROUP AVAILABILITY–CASE WITH A HIGH TRANSFORMER FAILURE RATE

Annual Transformer Failure Rate	Number of Spare Transformers	Group Availability	
		Markov Model of [11] (**)	Modified Markov Model of [15]
0.010 for both groups	0	0.74474	0.74474
	1	0.94657	0.94673
	2	0.98055	0.98061
	3	0.98428	0.98434
0.010 for Group 1 0.020 for Group 2 (*)	0	0.67435	0.67458
	1	0.91510	0.91554
	2	0.97005	0.97021
	3	0.97821	0.97833

(*) – Transformer failure rate in Group 2 is twice that of Group 1.
(**) – A weighted average transformer failure rate of .0135 was used [13 x .01 +7x 2 x.01)/20 = .0135].

Transformer rating = 7.5 MW
Transformer failure rate = 0.00372 or .010 outages/unit/year
Transformer repair time or lead time = 1.5 years
Spare transformer installation time = 4 weeks
Cost of one spare transformer = \$ 800000.00
Annual discount rate = 5%
Average customer interruption cost = \$ 5.00 /kwh (based on Hydro One's old surveys).

Two transformer failure rates, one low and one high were used in the study to see their impacts on the number of spare transformers required for the groups involved.

In this example, the reliability assessment was performed for a period of one year. On the other hand, the assessment can be done on a yearly basis during a planning period of more than one year when the sizes of the groups involved change from year to another.

A comparison of the group availability results obtained by Markov models of [11] and modified versions of Markov models of [15] are shown in Tables I–II for the low transformer failure rate and the high transformer failure rates respectively.

One can see from the group availability figures in Tables I–II that the Markov model of [11] and the modified version of Markov models of [15] produce the same results. Therefore, the Markov model of [11] can be used in handling cases with different transformer failure rates.

A summary of the group availability results is shown in Table III for the case with a low transformer failure rate.

TABLE III
SUMMARY OF THE GROUP AVAILABILITY–CASE WITH A LOW TRANSFORMER FAILURE RATE

Number of Spare Transformers	Group Availability		
	Group 1	Group 2	Both Groups
0	0.9302597	0.9618031	0.8948418
1	0.9936636	0.9972236	0.9882395
2	0.9962122	0.9979866	0.9940344
3	0.9962797	0.9979974	0.994271
4	0.9962811	0.9979975	0.9942785

TABLE IV
SUMMARY OF THE GROUP AVAILABILITY-CASE WITH A HIGH TRANSFORMER FAILURE RATE

Number of Spare Transformers	Group Availability		
	Group 1	Group 2	Both Groups
0	0.8247083	0.9011242	0.7447403
1	0.9727001	0.9892943	0.9465647
2	0.9887953	0.9944184	0.9805491
3	0.9899416	0.9946137	0.9842849
4	0.9900054	0.9946195	0.9846059
5	0.9900084		0.9846289

The following observations can be made regarding the group availability figures in Table III:

-Each group availability increases with the increase in the number of spare transformers.
-Each group availability saturates at a certain number of spare transformers (i.e., no significant changes in the group availability as the number of spare transformers increases).
-Group availability decreases as the group size increases.

If the saturation level of the group availability is used as a criterion (no changes in 3 digits after the decimal place) for estimating the required number of spare transformers, Group 1 or Group 2 requires 2 spare transformers while the combined group requires 3 spare transformers. Therefore, one spare transformer can be saved when the two groups are combined.

One should notice that the combined group availability is slightly lower than the individual group availability. Adding more spare transformers will not bring up the combined group availability to the level of the individual group availability. On the other hand, mobile unit transformers can be used to bring it up to the same level or even better.

Table IV provides the group availability results for the case with a high transformer failure rate. One can see from Table IV that the results follow the same trend as those in Table III. With a high transformer failure rate, the number of spare transformers will increase for each group. Group 1 requires 3 spare transformers, Group 2 requires 2 while the combined group requires 3 spare transformers. Therefore, 2 spare transformers can be saved when the two groups are combined.

The detailed assessment of the system cost criterion for the case with a low transformer failure rate is provided in the appendix. The summaries of the system cost results as a function of the number of spare transformers are given in Tables V–VI for the two transformer failure cases. One can see from Tables V–VI that the optimal numbers of spare transformers for Groups 1 and 2 and for both groups are almost the same as those obtained by the group availability criterion.

TABLE V
SUMMARY OF THE GROUP TOTAL ANNUAL COST–CASE WITH A LOW TRANSFORMER FAILURE RATE

Number of Spare Transformers	Total Annual Cost in $k		
	Group 1	Group 2	Both Groups
0	23,651.86	12,754.28	36,283.47
1	2,163.34	972.4	4,007.60
2	1,360.91	774.57	2,084.36
3	1,394.31	826.99	2,060.22
4	1,449.84	882.95	2,113.67

TABLE VI
SUMMARY OF THE GROUP TOTAL ANNUAL COST–CASE WITH A HIGH TRANSFORMER FAILURE RATE

Number of Spare Transformers	Total Annual Cost in $k		
	Group 1	Group 2	Both Groups
0	62,337.92	33,879.41	94,311.49
1	9,425.38	3,639.74	18,933.99
2	3,843.42	1,955.42	6,681.73
3	3,503.15	1,945.57	5,410.83
4	3,537.27	1,999.62	5,354.15
5	3,592.26		5,402.15
6			5,457.66

In summary, the two performance criteria produce very similar results in terms of the numbers of the spare transformers.

IV. CONCLUSION

This paper describes the reliability study performed recently for evaluating the reliability of distribution stations that are involved in spare transformer sharing. The study used stationary Markov models and two station performance criteria, namely the group availability criterion and the group total cost criterion, in the reliability evaluation.

The study results of the sample system demonstrate that the groups involved in the spare transformer sharing policy benefit in terms of reducing the required number of spare transformers while maintaining almost the same level of reliability. The results also show that the two performance criteria produce almost the same results and should complement one another when doing this type of the spare assessment.

APPENDIX

All probability figures in the tables below were produced by Markov models of [11]. The probabilities of levels 0, 1 and 2 are the probabilities of having all units in service, one unit out of service and two units out of service.

All annual cost figures in the tables below were computed using (1) and (2) in Section II and all costs are in thousands of dollars.

The results for the sample system using a low transformer failure rate of 0.0372 outages/transformer/year are provided below.

A. Group 1Results

Outage Level	Probability				
	0 spares	1 spare	2 spares	3 spares	4 spares
Level 0 (no outages)	0.9302597	0.9936636	0.9962122	0.9962797	0.9962811
Level 1 (single outages)	0.0674810	0.0062577	0.0037737	0.0037076	0.0037062
Level 2 (double outages)	0.00225927	7.8656E-05	1.4093E-05	1.275E-05	1.2727E-05

Cost Item	Annual Cost in $ k				
	0 spares	1 spare	2 spares	3 spares	4 spares
Annual cost of unsupplied energy with one transformer out	22167.52	2055.66	1239.66	1217.93	1217.48
Annual cost of unsupplied energy with two transformers out	1484.34	51.68	9.26	8.38	8.36
Total annual cost of unsupplied energy	23651.86	2107.34	1248.91	1226.31	1225.84
Annual cost of carrying charge	0.00	56.00	112.00	168.00	224.00
Total annual cost	23,651.86	2,163.34	1,360.91	1,394.31	1,449.84

B. Group 2 Results

Outage Level	Probability				
	0 spares	1 spare	2 spares	3 spares	4 spares
Level 0 (no outages)	0.9618031	0.9972236	0.9979866	0.9979974	0.9979975
Level 1 (single outages)	0.0375680	0.0027631	0.0020099	0.0019992	0.0019991
Level 2 (double outages)	0.000628889	1.329E-05	3.542E-06	3.433E-06	.4323E-06

Cost Item	Annual Cost in $ k				
	0 spares	1 spare	2 spares	3 spares	4 spares
Annual cost of unsupplied energy with one transformer out	12341.10	907.67	660.25	656.73	656.69
Annual cost of unsupplied energy with two transformers out	413.18	8.73	2.33	2.26	2.25
Total annual cost of unsupplied energy	12754.28	916.40	662.57	658.99	658.95
Annual cost of carrying charge	0.00	56.00	112.00	168.00	224.00
Total annual cost	12,754.28	972.40	774.57	826.99	882.95

C. Groups 1 and 2 Results

Outage Level	Probability				
	0 spare	1 spare	2 spares	3 spares	4 spares
Level 0 (no outages)	0.8948418	0.9882395	0.9940344	0.9942710	0.9942785
Level 1 (single outages)	0.0998643	0.0114918	0.0059271	0.0056979	0.0056905
Level 2 (double outages)	0.0052938	0.0002687	3.8537E-05	3.114E-05	3.0943E-05

Cost Item	Annual Cost in $ k				
	0 spares	1 spare	2 spares	3 Spares	4 spares
Annual cost of unsupplied energy with one transformer out	32805.44	3775.05	1947.04	1871.76	1869.34
Annual cost of unsupplied energy with two transformers out	3478.03	176.55	25.32	20.46	20.33
Total annual cost of unsupplied energy	36283.47	3951.60	1972.36	1892.22	1889.67
Annual cost of carrying charge	0.00	56.00	112.00	168.00	224.00
Total annual cost	36,283.47	4,007.60	2,084.36	2,060.22	2,113.67

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Gomaa A. Hamoud (Senior Member, IEEE) received the B.Sc. degrees in electrical engineering and applied mathematics from Cairo University, Giza, Egypt, in 1970 and 1972, respectively, the M.Sc. degree in applied mathematics from the University of Saskatchewan, Saskatoon, SK, Canada, in 1976, and the M.Sc. and the Ph.D. degrees in electrical engineering from the University of Saskatchewan, Saskatoon, SK, Canada, in 1978 and 1981, respectively. In 1981, he joined Hydro One (formerly Ontario Hydro). He is currently a Senior Network Management Engineer with Special Studies Department, System Planning Division. His research interests include reliability modeling and evaluation of power systems, transfer capability assessment, risk assessment, asset management and power system planning. He is a member of the Ontario Association of Professional Engineers.