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Another Look at the Use of Mobile Unit Substations in Customer Delivery Systems

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SUMMARY

In last few years, a number of reliability studies have been carried out at Hydro One to evaluate the economic benefits from using mobile unit substations (MUS's) in customer delivery systems (CDS's). In these studies, steady state Markov models were used to evaluate the economic benefits from using MUS's in CDS's. One of these studies was performed in 2013 to find out whether the use of the MUS in redundant customer delivery systems was justified from the economic point of view when the station two companion transformers were out of service. The study used 3 Markov models to represent Class II transformer failures (minor failures), Class I transformer failures (major failures) and the usage of the MUS. The benefit from the MUS was evaluated by convolving each transformer failure model with the MUS model. A cost /benefit analysis was performed to answer the question.

Recently, some additional work has been done on the same subject. In this work, a combined Markov model was developed to represent both Class I and Class II failures. Then, the economic benefit from the MUS was evaluated by convolving the combined Markov model with the MUS model. The new method of assessment was found to produce almost the same results with some advantages over the earlier method of assessment.

This paper describes a simple probabilistic method for evaluating the benefit from the use of the MUS in CDS's. The proposed method uses one Markov model to represent Class I and Class II transformer failures and the MUS is represented by a two state Markov model. The two models are then convolved to produce one formula for calculating the benefit from the MUS when the two station companion transformers are out of service. A sample of the Hydro One's customer delivery systems is used to illustrate the proposed method of assessment and to compare the results with the previously assessment method.

KEYWORDS

Customer delivery system, mobile unit substation, Markov model, transformer failures, cost/benefit analysis, probability of failure.

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I.0 INTRODUCTION

Mobile unit substations (MUS's) have been used in distribution systems for a long time to avoid long power outages to customers [1]-[9]. The MUS can carry the entire station load since the station load is relatively small. On the other hand, the use of MUS's in CDS's has been limited due to their limited ratings and because most of the delivery systems have been designed with some redundancy (i.e. the loss of one transformer will not result in any load loss to customers). Since the transformers used in CDS's have much higher ratings than those used in distribution stations and the MUS cannot carry the entire station load. In some situations, MUS's can be used when transformer failures occur at a customer delivery system and the system load cannot be transferred partially or entirely to the neighbouring stations. The MUS may or may not carry the entire station load depending on its size and in the worst case, the MUS could supply at least the most critical loads at the station. In general, MUS's can be used in a redundant customer delivery system (system with two transformers operated in parallel) for the following reasons:

1. To replace temporarily a failed unit when the companion unit is out of service for planned work.
2. To replace the two station units when both units experience failures.
3. To replace temporarily a failed unit when the station load exceeds the station limited time rating.
4. As a stop gap to delay construction of a new load station.
5. To replace temporarily a transformer when it is taken out of service for repair or maintenance work in order to minimize the frequency of supply interruptions to the customer that has a performance-based contract in order to avoid the interruption penalty cost.

A number of reliability studies have been performed at Hydro One to evaluate the benefits from using MUS's in some of the above mentioned situations [10]-[12]. One reliability study was performed in [12] to find out whether the use of the MUS in redundant customer delivery systems was justified from the economic point of view when the station two companion transformers were out of service. In that study, two Markov models for representing Class I and Class II transformer failures and one Markov model for representing the MUS were used when calculating the benefit from the MUS.

Recently, one Markov model for representing Class I and Class II transformer failures was used for spare analysis of distribution power transformers [13]. The same model was used in another study to represent Class I and Class II failures for a group of similar power transformers used in CDS's. This study used the one Markov model in evaluating the benefit from using the MUS. The purpose of this paper is to describe the new study and to compare the new results with those obtained earlier in [12]. In fact, the assessment method presented in this paper can be considered an alternative method to the method of [12] in evaluating the benefit from the use of the MUS in CDSs. In addition, the proposed method has some advantages over the method of [12] as demonstrated later in the paper.

2.0 HYDRO ONE CUSTOMER DELIVERY SYSTEMS

The customer delivery system (CDS) of Hydro One 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. The CDS can be a simple radial supply system or can be designed with redundancy (a meshed type supply system). The supply system known as the Dual Element Spot Network (DESN) arrangement has been adopted by Hydro One as a basic design for supplying loads in the 100-200 MW range. A typical DESN arrangement is shown in Fig. 1. The system has two high voltage supply lines (components 1 and 2), two power transformers (components 3 and 4), two low voltage buses (components 8 and 9), two low voltage transformer breakers (components 5 and 6), a bus-tie breaker (component 7) and up to twelve feeder breakers (not shown in Fig. 1). The bus-tie breaker is closed under normal operation. Feeders on one bus can be transferred to the companion bus in case of a bus or feeder breaker outage using feeder tie switches (component 10).

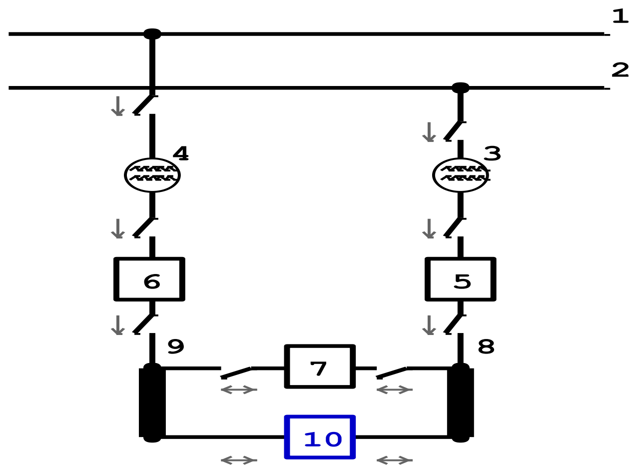

Fig. 1 Single Line Diagram of a DESN Station

Transformers at a DESN station can fail randomly and the failure can be minor or major. The minor failure is short and the repair is done at site and is referred to as a Class II failure. The major failure is long and the failed unit can be either repaired or replaced depending on the nature of the outage. The major failure is referred to as a Class I failure. There is another type of transformer failures (non-random failures) caused by aging and is not used in this assessment.

When a transformer at a DESN station fails, the companion transformer should be able to carry the entire load without overloads. When both transformers fail, the entire station load is lost. The duration of the load loss will depend on the type of failure and the availability of spare units. Some critical loads at the station may not tolerate an outage that lasts for days or weeks and the use of the MUS may help in this regard.

3.0 ONE MARKOV MODEL FOR CLASS I AND CLASS II TRANSFORMER FAILURES

One Markov model is used to represent both Class I and Class II transformer failures [13]. The model assumes that both Class I and Class II failures are random and their failure rates are constant over a given period of time. Fig. 2 shows the one Markov model for a group of n similar transformer units with one regular spare transformer (RST). In this model, a unit can fail either Class I or Class II at any point in time.

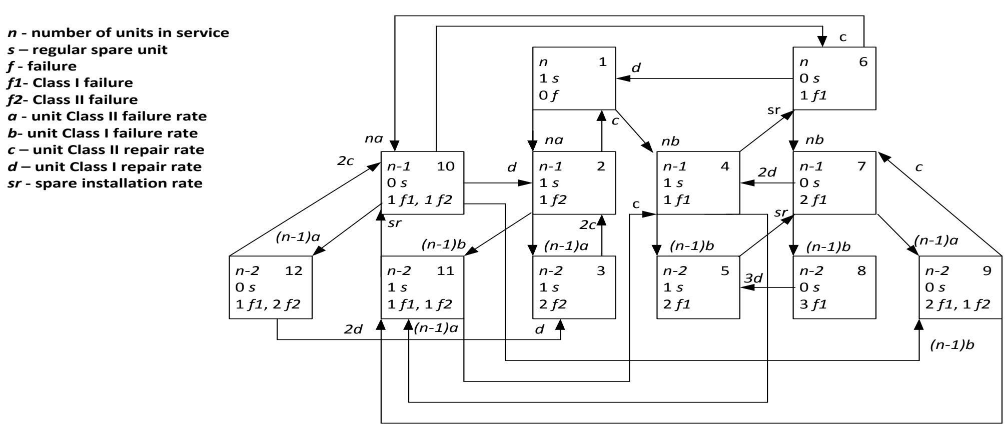

Fig. 2 Markov Model for Class I and Class II Failures for a Group
of *n* Units with One Regular Spare Transformer

The following assumptions have been made in the model of Fig. 2:
1. Transformers fail independently and all failures are assumed to be random.
2. Only one unit can fail either Class I or Class II at any point in time.
3. Failures due to aging are excluded in the assessment since their modelling is different.
4. No more than 3 failures can take place in any one of the system states.
5. Repair to Class II failed units can start at any time.
6. Repair to Class I failed units starts when there are *n* units in service, or there is no RST available.
7. RST’s are installed before doing any repair to Class I failed units.
8. RST’s are used only to replace Class I failed units

The above assumptions are reasonable and agree with Hydro One’s practices when dealing with Class I and Class II transformer failures. The description of all states in Fig. 2 is given in [13].

The state probabilities can be obtained by solving a set of linear equations (12 equations). The linear equations are formed using the total frequency balancing approach [14].

Assume that all load stations are of the DESN type, then, the following remarks can be made regarding the states in Fig. 2:

In each one of States 2, 4, 7 and 10, there are n-1 units in service and therefore, there will be no load loss at any one of the DESN stations.

On the other hand, in each one of States 3, 5, 8, 9, 11 and 12, there are n-2 units in service and two or 3 units out of service. If two out of service units happen to occur at the same DESN station, there will be a load loss at the station. The probability of losing two units at a DESN station is given by the following expression:

$$T_i = P_i / {}^{n}C_2 \qquad (1)$$

Where:
P_i = Probability of State i, i = 3, 5, 8, 9, 11 and 12
T_i = Probability of losing two units at a DESN station in State i, i = 3, 5, 8, 9, 11 and 12
${}^{n}C_2$ = Number of ways a pair of units can be formed from a group of n units and is equal to $n(n-1)/2$.

The value of P_i is obtained from the model of Fig. 2.

4.0 EVALUATING THE BENEFIT FROM THE MUS

Equation (1) gives the probability of losing the entire DESN station load while being in State i. Because of the limited capability of the MUS, only a portion of the station load (i.e. critical load) can be supplied by the MUS. The reduction in the annual customer interruption cost due to the use of the MUS at a DESN station is calculated using the following expression:

$$RACIC = \sum_{i=1}^{m} T_i \, 8760 \, p(1)_i \, R \, LF \;\; CIC \qquad \text{\$/station/year} \qquad (2)$$

Where:
$RACIC$ = Reduction in annual customer interruption cost in dollars at one DESN station
R = Rating of the MUS in MW
$p(1)_i$ = Probability of the in use of the MUS in State i, i = 3, 5, 8, 9, 11 and 12.
LF =Load factor of the station critical load to be supplied
CIC =Customer interruption cost in \$/MWh at the station
m = Number of Markov states where the MUS is used.

The parameter, $p(1)_i$, in Equation (2) is determined with the help of the MUS model in Fig. 3. States 0 and 1 of Fig. 3 represent the not in use and the in use states of the MUS respectively. Initially, the MUS will be in State 0 and after the deployment, the MUS will be in State 1. The MUS will stay in

State 1 until the failed unit is either repaired (Class II failure) or replaced (Class I Failure). The transition rate from State 0 to State 1 is equal to the deployment rate of the MUS. On the other hand, the transition rate from State 1 to State 0 should account for the MUS deployment time and the time required either to repair or to replace the failed unit. The probabilities of being in States 0 and 1 are given by:

$$p(0) = u/ (s + u)$$
$$p(1) = s/ (s + u) \qquad (3)$$

Where:

$p(0)$= Probability of being in State 0

$p(1)$ = Probability of being in State 1

s = Annual deployment rate of the MUS and is equal to the reciprocal of the deployment time in years.

u =Annual in use rate of the MUS and is equal to the reciprocal of the difference expressed in years between the time required either to repair or to replace the failed unit and the MUS deployment time.

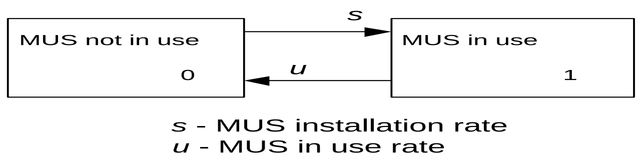

Fig. 3 Markov Model for MUS

The value of parameter, u, can also be affected if there is a restriction on the operating time for the MUS in order to avoid the over use of the unit. In this case, the maximum operating time for the MUS must be included when calculating the parameter u.

Depending on the deployment time for the MUS, the values of $p(0)$ and $p(1)$ can vary. For example, if the deployment time is zero, then $p(0)$ becomes 0 and $p(1)$ becomes 1. When the deployment time becomes equal to the unit repair time, $p(0)$ and $p(1)$ become 1 and 0 respectively.

It is worth mentioning that in Equation (3), the deployment time of the MUS must be shorter than the repair time of the unit or the deployment time of the RST, otherwise, there will be no benefit from the MUS.

The value of $p(1)_i$ is calculated using Equation (3) for each state used in Equation (2) as follows:

In State 3, the MUS can be used to replace one of the Class II failed units and $p(1)_3$ is equal to $s/(s+t)$.
In State 5, the MUS can be used to replace one of the Class I failed units and $p(1)_5$ is equal to $s/(s+v)$.
In State 8, the MUS can be used to replace one of two Class I failed units and $p(1)_8$ is equal to $s/(s+w)$.
In State 9, the MUS can be used to replace the Class II failed unit and $p(1)_9$ is equal to $s/(s+t)$.
In State 11, the MUS can be used to replace either the Class II failed unit or Class I failed unit and $p(1)_{11}$ is equal to $s/(s+x)$.
In State 12, the MUS can be used to replace one of the two Class II failed units and $p(1)_{12}$ is equal to $s/(s+t)$.

The parameters t, v, w and x are defined as follows:

t = The reciprocal of the difference, expressed in years, between the unit Class II repair time and the MUS deployment time.

v = The reciprocal of the difference, expressed in years, between the RST installation time and the MUS deployment time.

w =The reciprocal of the difference, expressed in years, between the time required to get a replacement unit for the Class I failed unit and the MUS deployment time.

x = The reciprocal of the difference, expressed in years, between the minimum of the time required to repair Class II unit and the deployment time for the RST and the MUS deployment time.

5.0 COST/BENEFIT ANALYSIS FOR USE OF THE MUS IN DESN STATIONS

The cost of one MUS can range from 2 to 4 million dollars depending on the size and the voltage level. For the purpose of this analysis, the annual cost of carrying an MUS (*ACC*) is simply the product of the MUS cost and the annual discount rate.

The annual benefit from the use of the MUS is calculated for each DESN station using Equation (2). The total annual benefit will be the sum of all individual station annual benefits.

Having obtained the above two cost components, the next step is to compare them to determine whether the MUS is justified or not.

6.0 ILLUSTRATING EXAMPLE

The Markov model described above is used to calculate the benefit from using an MUS for the same example used in [12] (a group of 100, 230 kV transformers used at 50 Hydro One DESN stations). The Class I and II failure data used in the assessment was based on the performance of all Hydro One's 230 kV step down transformers over the period Jan 1990 to July 2011. The failure data used in the assessment is provided in Table I.

TABLE I
FAILURE DATA USED IN THE ASSESSMENT

Failure Class	Annual Failure Rate failures/unit/year	Failure Duration hours/failure
I	.00378279	8760
II	.225599	59.051667

Notes:
1. All Class II failures with duration greater than 50 days are excluded.
2. Failure duration for Class I failures represents the average unit repair time or the time required to acquire new unit.

The following assumptions were made in the study:

- All DESN stations are identical.
- Al DESN stations have MUS capabilities and the MUS can supply a peak load up to 20 MW.

Tables II and III provide the other data and information used in the assessment.

TABLE II
MUS AND RST DATA USED IN THE ASSESSMENT

Size of MUS	20 MVA
Cost of MUS	$ 4 millions
Deployment time for the MUS	2 days
Deployment time for the RST	28 days
Time required to get a replacement unit if the RST is not available	50 days
Reliability indices for the RST	Same as regular units

Using the information in Tables II and III, the annual cost of carrying the MUS is found to be $ 200 k. The Markov states in Fig. 2 contributing to the benefit from MUS's are States 3, 5, 8, 9, 11 and 12. The probabilities of those states and their contributions to the benefit from the MUS are provided in Table IV. The results in Table IV show that not only the state probability is contributing to the benefit from the MUS but also the probability of the in use of the MUS based on Equation (2). This is clearly demonstrated in Table IV for States 3 and 8. The two state contributions are quite different because the probabilities of the in use of the MUS are different in the two states.

The annual benefit from using the MUS at 50 stations is found to be $ 140.75 k which means that the MUS is not justified in the case study.

TABLE III
OTHER RELEVANT DATA USED IN THE ASSESSMENT

Load factor of critical station load	.75
Customer interruption cost	$ 10 /KWh
Annual discount rate in %	5
Number of DESN stations with the MUS capability	50
Number of transformers at all DESN stations	100

7.0 COMPARISON OF METHODS

The method of [12] was used to calculate the annual benefit from the MUS. The method used two Markov models to represent Class I and Class II transformer failures. The parameter, *Min*, used in Equations (10) and (11) of [12] for calculating the contributions to the benefits from the overlap of Class II and Class I failures and the overlap of Class I and Class II failures was slightly modified. The deployment time for the MUS needs to be subtracted from the parameter, *Min*, since the actual usage time for the MUS is *Min* minus the deployment time for the MUS.

TABLE IV
PROBABILITIES OF MARKOV STATES AND THEIR
CONTRIBUTIONS TO THE MUS BENEFIT

Markov State #	State Probability	State Contribution $/station/year
3	0.0065676	326.28
5	0.0019155	472.15
8	0.0054793	1396.31
9	0.0066016	327.97
11	0.003437	170.75
12	0.0024471	121.57

The illustrating example was used to compare the results of the method of [12] and the method proposed in this paper. Equation (2) was used to calculate the benefit from the MUS per station and the total benefit is obtained by multiplying the individual station benefit by the number of stations.

The results of the method of [12] and the proposed method are shown in Table V. As can be seen from Table V, the two results are in good agreement.

TABLE V
COMPARISON OF TWO METHODS

Modelling Method	Annual Benefit in k $
Two Markov Models	141.231
One Markov Model	140.752

In summary, the method based on one Markov model almost produces the same results as the one based on three Markov models when evaluating the benefit from the use of the MUS in CDS's. In addition, the proposed assessment method has the following two advantages over the method of [12]:

1. It uses only one simple formula to calculate the benefit from the MUS when compared to the method of [12].
2. It can easily be expanded to handle cases where the MUS is used for one and two transformer stations.

8.0 CONCLUSIONS

A one Markov model has been used in calculating the benefit from using the MUS at DESN stations when the two station transformers are out of service. The benefit is calculated in terms of a reduction in customer interruption cost experienced by some customers at stations. The one Markov model results for the case study show that its results are in excellent agreement with the two Markov models results and therefore, it can be used in evaluating the benefits for use the MUS'S in DESN stations.

In addition to the good accuracy of the new assessment method, the method has the advantages that it uses only one simple formula in calculating the benefit from using the MUS in DESN stations and can easily be expanded to handle the use of the MUS at DESN and non-DESN stations.

BIBLIOGRAPHY

[1] W. Li, E. Vaahedi and Y. Mansour, "Determining number and timing of substation spare transformers using a probabilistic cost analysis approach," IEEE Transactions on power delivery, Vol. 14, No. 3, July 1999.

[2] J. M. Nahman and M. R. Tanaskovic, "Probability models for optimal sparing of distribution network transformers," IEEE Transactions on Power Delivery, Vol. 24, Issue 2, April 2009, pp. 758-763.

[3] A. A. Chowdhury and D. O. Koval, "Development of probabilistic models for computing optimal distribution substation spare transformers," IEEE Transactions on Industry Applications, Vol. 41, Issue 6, November 2005, pp. 1493-1498.

[4] A. M. Leite da Silva, J. G. de Carvalho and A. A. Chowdhury, "Probabilistic methodologies for determining the optimal number of substation spare transformers," IEEE Transactions on Power Systems, Vol. 25, Issue 1, February 2010, pp. 68-77.

[5] G. A. Hamoud, "Use of Markov models in assessing spare transformer requirements for distribution stations," IEEE Transactions on Power Systems, Vol. 27, No. 2, May 2012 , pp. 1098 - 1105.

[6] A. M. Leite da Silva, J. G. de Carvalho Costa, K. G. Machado, L. L. de Souza and R. A. Gonzalez-Fernandez, "Probabilistic methodologies for optimizing the optimal number and timing of substation spare transformers," Paper has been accepted for inclusion in a future issue of IEEE Transactions on Power Systems.

[7] V. I. Kogan, C. j. Roger and D. E. Tipton "Substation distribution transformers failures and spares", IEEE Transactions on Power Systems", Vol. 11, Number 4, Nov. 1996, pp. 1906 -1912.

[8] J. G. C. Costa and A. M. Leite da Silva, "Monte Carlo simulation to assess the optimum number of distribution spare transformers," 10th International Conference on PMAPS- probability methods applied to power systems," May 25-29, Rincon, Puerto Rico, 2008.

[9] G. A. Hamoud, "Assessment of spare transformer requirements for distribution stations," IEEE Transactions on Power Systems, Vol. 26, Number 1, February 2011, pp. 174 - 180.

[10] G. Hamoud, "Cost/benefit analysis for use of mobile unit substations in customer delivery systems," Power Engineering Society General Meeting, 2006, IEEE, June 18 – 22, pages 1-5.

[11] G. Hamoud," Use of Mobile Unit Transformers in High Voltage Load Stations," PMAPS, 2008.

[12] G. Hamoud and C. Yiu, "Use of Mobile Unit Substation in Redundant Customer Delivery Systems', IEEE Transactions on Power Systems, Vol. 29, No. 3, May 2014, pp. 1403-1409.

[13] G. Hamoud and C. Yiu, "One Markov Model for Spare Analysis of Distribution Power Transformers", Paper has been Accepted for Inclusion in a Future Issue of this Journal.

[14] R. Billinton and R. N. Allan, "Reliability Evaluation of Power Systems", 2nd Edition, Plenum Press, London, 1996.