Prioritization of network transformers in electrical distribution system by considering social welfare index

A. Prudhi Krishna, P. Srinivasa Varma, R. B. R Prakash, V. Kiran Babu
Department of EEE, Koneru Lakshmaiah Education Foundation, India

ABSTRACT
To supply a meshed distribution system, network transformers are required. When few transformers are not in service, they must be repaired or replaced. A method is proposed for prioritizing the transformers considering the critical loads. Repair or replacement of transformers can be done by giving priority based on risk reduction. By addressing the possibility of network collapse due to failure of the feeder and impacted customers, risk can be predicted where the loads are extremely used at feeders section, network transformers and secondary mains. To select the transformer that needs to be replaced quickly and economically, an algorithm is proposed and it was tested on IEEE test system using GridLAB-D, MATLAB softwares. An index is proposed to give priority to emergency needs like hospitals and water pumping stations. Replacement or repair can be done by prioritizing network transformers incorporating social welfare index.

Keywords:
Network transformers
Power system restoration
Risk reduction

1. INTRODUCTION
In order to reduce the duration of major failures in bulk power supplies, restoration actions are required. Network transformers are required to feed the heavily meshed secondary grid distribution systems. In the case of outages of these network transformers, replacement or repair must be done to get those network transformers into the service. Replacement or repair of the network transformers can be easily done if they are prioritized. Priority can be given to the transformers based on the number of customers affected. Prioritizing the network transformers can be done by using a risk index [1] algorithm for mesh type distribution networks at the time of normal loading conditions. Transformer outages may happen due to overload of an equipments or tank leakages or damage in protection or due to maintenance etc. These can be identified by using a bonding method [2], line outage distribution factors (LODF) [3] and power flows [4]. In real time, distribution transformers are monitored by using RMS (Real time Monitoring System) integrated with PLC (Power Line Carrier) technology. From this, status of transformer, terminal voltages, temperatures, loading etc can be known easily. Z bus matrix [5] is preferred for large meshed underground networks. Loads near the network transformers can be easily identified with Z bus matrix construction.

Flow violations can easily calculated for branch, generating unit and load outages using bounding method [6]. In general LODF’s are used in transmission systems to find the line flows after line outage [7], to calculate multiple line outages for system security [8], and contingency analysis for multiple line outages [9-10]. For contingency analysis, many power flows methods have been proposed to get fast and efficient solution [11], and to execute contingency list independently [12]. Even though by providing sufficient data to the contingency tools as mentioned above, no tools can able to prioritize the return of network transformers. So by using risk index [1], priority can be provided to the transformers in normal loading conditions.
In the case of emergency conditions, priority of the transformers may not be possible as per risk index terms. Priority must be given as per critical loads and constraints.

In order to prioritize the network transformers, social welfare index is proposed such that all the network transformers are given priority by considering social issues and benefits. Later remaining network transformers can be prioritized as per normal loading conditions. The above algorithm has been tested on IEEE 342 Node Low Voltage Network Test System (LVNTS) [13-16]. LVNTS is flexible for new algorithms and analysis can be easily done for distribution networks. It is a heavily meshed network systems, system with more parallel transformers and on parallel low voltage cables. The main contributions of the paper are:

a) To rank the priority of distribution transformers, a rigorous and robust algorithm is proposed by considering social welfare index.

b) To verify the proposed algorithm to rank distribution transformers, of IEEE 342 node low voltage networked test system.

A computer program is developed to compute the load contribution, while running the program by power flow, reliability evaluation and replacing one transformer at a time [17]. Prioritizing the return of network transformers, the service can be restored according to the number of customers per network. This paper is organised as follows: Initially in this section, the introduction and literature survey is discussed. Next in Section 2, the risk index formulation for transformers under normal loading conditions is discussed. Section 3 presents the social welfare index formulation for transformers under emergency conditions. In Section 4, the social welfare index algorithm to prioritize the transformers under emergency conditions is explained. In Section 5, sample calculations are shown to find the risk index of a transformer. In Section 6 the results are analysed and in Section 7, the conclusion for work done is presented.

2. RISK INDEX FORMULATION

Prediciting the loads in networks and network reliability performance, the restoration of failed transformers depends on experience and tools developed in recent years. Here risk can be expressed in different terms such as:

a) Number of customers with interrupted service in a specific time period.
b) Customers who would have been exposed to low voltages.
c) Financial risk resulting from loss of power.

Once, the transformer is once prioritize and return to the service, the risk of the transformer is identified and the process is repeated for prioritizing subsequent return of other transformers, this must be done by examining the all failed transformers.

Failures can be caused by overloading of transformers and it can be prevented by prioritizing the restoration of failed transformers. This method evades the costly and ineffective dispatch of personnel for low priority transformers, and this allows the resources to be allocated for higher priority transformers. Restoring the transformer into service, other transformers results in lowering the loads and therefore the likelihood of the failures get decreased. The sum of the number of customers impact due to failure of transformers, feeders and secondary mains is expressed as risk index.

\[
\text{Risk Index} = \delta_1 + \delta_2 + \delta_3
\]

Where \(\delta_1\) represents the number of consumers interrupted due to overload in transformers, \(\delta_2\) represents the number of consumers interrupted due to overload in primary feeders; \(\delta_3\) represents the number of consumers interrupted due to overload in secondary mains. Alpha (\(\alpha\)) is the factor which measures the relative load of each of the equipment and it is calculated as

\[
\alpha = \frac{\text{equipment loading}}{\text{equipment rating}}
\]

The number of consumers interrupted due to overload in transformers (\(\delta_1\)) is computed as

\[
\delta_1 = NC \left( \sum_{j=1}^{NT} f(\alpha_j) \right)
\]

Where,

\(\text{NC}\) : number of customers supplied by the network
\(\text{NT}\) : number of transformers which pickup extra load when a transformer is failed
\(f(\alpha_j)\) : Probability of a failed load with an in service transformer engaging in network collapse
\[ f(\propto_j) = f_1(\propto_j)(c_j) \] (4)

Where
\[ f_1(\propto_j) : \text{The probability of transformer failing at its relative load } \propto_j \]
\[ c_j : \text{Conditional probability of collapsing a network due to the transformer j failure and the feeder that serves it} \]

The number of customers interrupted due to overload in feeders (\( \delta_2 \)) is computed as
\[ \delta_2 = NC(\sum_{j=1}^{NF} g(\propto_k)) \] (5)

Where
\[ NC : \text{number of consumers supplied by the network} \]
\[ NF : \text{number of overloaded feeders} \]
\[ g(\propto_k) : \text{Probability of an in service feeder failure engaging in network collapse} \]

\[ g(\propto_k) = g_1(\propto_k)(d_k) \] (6)

Where
\[ g_1(\propto_k) : \text{Probability of feeder failure at its relative load } \propto_k \]
\[ d_k : \text{Conditional probability of collapsing a network after feeder k failure} \]

The number of customers interrupted due to overload in secondary mains (\( \delta_3 \))
\[ \delta_3 = \frac{\text{Increment in Load}}{\text{Average Load per Customer}} \] (7)

By evaluating the risk associated with number of devices, the restoration of failed transformers can be planned through the described approach. The variable \( d_k \) is the probability of network collapse after the failure at feeder ‘k’ which is similar to that \( c_j \) is the conditional probability of network collapse after the failure of transformer ‘j’ fed by the feeder ‘k’.

Ranking is done for all the out of service transformers, risk is calculated and priority is given to restore the transformers from the resulting list.

3. **SOCIAL WELFARE INDEX FORMULATION**

Prioritizing of transformers can be done easily by using risk index at normal loading conditions where in the case of emergency conditions priority may not be given to network transformers due to social issues and constraints. During emergency conditions, prioritizing of network transformers must be given to the transformers which supply the power to hospitals, water pumping stations etc rather than supplying the power based on number of customers. Repair and replacement of network transformers is done based on critical loads and remaining transformers are prioritized as per loading conditions. Social Welfare Index (SWI) is defined as shown below:

\[ \text{SWI} = (\text{No. of hospitals} \times 1) + (\text{No. of water stations} \times 0.9) \] (8)

4. **SOCIAL WELFARE INDEX ALGORITHM**

The flow chart of the algorithm is shown in the Figure 1. In the computer program all the equations that are related to the risk index and social welfare index are implemented.

Under real time system conditions also, this program can be implemented. The data required for input to the program are feeders out, secondary cables that are burnt out and transformers that are out of service. Operations can be done till the last minute decisions are taken on system hardening before the next day heat wave. The operations are:

a) For transformers, feeders and secondary mains compute ‘\( \propto \)’ before and after the restoration of an out of service transformer.

b) Analyzing failure rates of individual components.

c) For transformers and feeders, computing the probabilities of contingencies (\( c_j, d_k \)).
5. SAMPLE CALCULATIONS

Calculations are shown for the transformer by considering T70 is out of service. To calculate risk index for T70, as shown in (3), (5), (7) need to be solved. Total number of customers (NC) for LVNTS is 624. When transformer T70 is out of service, the number of transformers which bear additional load (NT) is 38. Probability values of transformers and feeders can be computed by their transformer failure rates and feeder failure rates respectively through curve fitting method [1].

From Table 1, the obtained probability and conditional probability values of transformers are substituted in (4), to obtain overall probability as shown.

$$\left(\sum_{j=1}^{38} f(\alpha_j)\right) = 0.031701$$

Therefore from (3),

$$\delta_1 = 624 \times 0.031701 = 20$$

When T70 is failed, the number of feeders that are overloaded (NF) is 6. From the Table 2, the obtained probability and conditional probability values of feeders are substituted in (6), then.

| Transforms | $f_i(\alpha_j)$ | $(c_j)$ |
|------------|----------------|--------|
| T6         | 0.001439       | 0.0546 |
| T9         | 0.003025       | 0.611  |
| T11        | 0.003652       | 0.1314 |
| T12        | 0.003733       | 0.1306 |
| T18        | 0.008485       | 0.288  |
| T20        | 0.001077       | 0.0355 |
| T22        | 0.007678       | 0.2456 |
| T24        | 0.009147       | 0.2865 |
| T25        | 0.000999       | 0.0299 |
| T26        | 0.009097       | 0.2638 |
| T30        | 0.007167       | 0.2006 |
| T31        | 0.007775       | 0.2099 |
| T33        | 0.00992        | 0.2579 |
| T34        | 0.007885       | 0.1971 |
| T37        | 0.006117       | 0.1468 |
| T38        | 0.0053         | 0.121  |
| T39        | 0.009999       | 0.0219 |
| T43        | 0.010135       | 0.2128 |
| T44        | 0.008239       | 0.1647 |
| T45        | 0.008609       | 0.1635 |
| T46        | 0.003875       | 0.0697 |
| T48        | 0.0048055      | 0.1369 |
| T49        | 0.00832        | 0.1331 |
| T50        | 0.000999       | 0.0149 |
| T51        | 0.009971       | 0.1395 |
| T53        | 0.004781       | 0.0621 |
| T54        | 0.00435        | 0.0521 |
| T56        | 0.007274       | 0.08001|
| T57        | 0.00635        | 0.0635 |
| T59        | 0.010121       | 0.0910 |
| T60        | 0.009999       | 0.00799|
| T61        | 0.007026       | 0.0491 |
| T62        | 0.004979       | 0.0298 |
| T64        | 0.006217       | 0.0310 |
| T66        | 0.009999       | 0.0039 |
| T67        | 0.006377       | 0.0191 |
| T68        | 0.00624        | 0.0124 |
| T69        | 0.005314       | 0.0053 |

Figure 1. Flow chart for social welfare index algorithm
Table 2. Probabilities and Cumulative Probabilities of Feeders that are Overloaded

| Feeders that are overloaded | \( g(\kappa_k) \) | \( (d_k) \) |
|----------------------------|-----------------|--------|
| F2                         | 0.0047          | 0.02824|
| F3                         | 0.0043          | 0.02174|
| F4                         | 0.0046          | 0.0184 |
| F6                         | 0.0053          | 0.01602|
| F7                         | 0.0076          | 0.01529|
| F8                         | 0.0041          | 0.0041 |

\[ \sum_{j=1}^{6} g(\kappa_k) = 0.000532 \]

Therefore from (5)

\[ \delta_2 = 624 \times 0.000532 = 1 \]

Average load per customer in LVNTS is 67.64 kW and Increment in load is 100 kW. By using (7), we get \( \delta_3 \) as 2. Therefore by using the above obtained values, risk index value of T70 transformer is 23. Similarly Risk index is calculated for remaining transformers from the above process.

6. RESULTS

The Table 3 represents the results for ranking of 68 transformers under normal loading conditions by including risk index. Network transformers T5, T11, T32, and T57 supply the hospitals and water stations which are represented in Table 2. From the above obtained results the following transformers are removed and they are prioritized as per social welfare index.

Table 3. Ranking of Transformers Under Normal Loading Conditions

| Rank of the Transformer | Name of the Transformer | Risk Index Value |
|-------------------------|-------------------------|------------------|
| 1                       | T43                     | 30               |
| 2                       | T46                     | 27               |
| 3                       | T49                     | 27               |
| 4                       | T51                     | 27               |
| 5                       | T41                     | 26               |
| 6                       | T56                     | 26               |
| 7                       | T64                     | 26               |
| 8                       | T24                     | 25               |
| 9                       | T42                     | 25               |
| 10                      | T13                     | 24               |
| 11                      | T26                     | 24               |
| 12                      | T40                     | 24               |
| 13                      | T44                     | 24               |
| 14                      | T45                     | 24               |
| 15                      | T52                     | 24               |
| 16                      | T62                     | 24               |
| 17                      | T67                     | 24               |
| 18                      | T29                     | 23               |
| 19                      | T35                     | 23               |
| 20                      | T36                     | 23               |
| 21                      | T48                     | 23               |
| 22                      | T57                     | 23               |
| 23                      | T59                     | 23               |
| 24                      | T70                     | 23               |
| 25                      | T28                     | 22               |
| 26                      | T38                     | 22               |
| 27                      | T47                     | 22               |
| 28                      | T58                     | 22               |
| 29                      | T68                     | 22               |
| 30                      | T34                     | 21               |
| 31                      | T63                     | 21               |
| 32                      | T65                     | 21               |
| 33                      | T33                     | 20               |
| 34                      | T61                     | 20               |
| 35                      | T3                      | 19               |
| 36                      | T27                     | 19               |
| 37                      | T37                     | 19               |
| 38                      | T55                     | 19               |
From the Table 3 calculated indices the transformer with highest index value is given the first priority and the transformer having least index value is given as least priority. Based on the indices values, prioritizing of transformers have been done as shown in Table 4. Prioritization of Transformers with SWI values as shown in Table 5.

### Table 4. Prioritization of Transformers based on Social Welfare Index

| Rank | Name of the Transformer | Social Welfare Index values |
|------|-------------------------|----------------------------|
| T5   | 3                       | 2.9                        |
| T11  | 2                       | 2.8                        |
| T32  | 1                       | 1.9                        |
| T57  | 1                       | 3.9                        |

### Table 5. Prioritization of Transformers with SWI Values

| Rank | Name of the Transformer | Social Welfare Index values |
|------|-------------------------|----------------------------|
| 1    | T57                     | 3.9                        |
| 2    | T5                      | 2.9                        |
| 3    | T11                     | 2.8                        |
| 4    | T32                     | 1.9                        |

Prioritizing of network transformers have been done according to the social welfare index at the time of emergency conditions for all 68 transformers can be observed from the Table 6.
Table 6. Prioritization of Network Transformers based on SWI and Risk Index

| Rank of the Transformer | Name of the Transformer |
|-------------------------|-------------------------|
| 1                       | T57                     |
| 2                       | T5                      |
| 3                       | T11                     |
| 4                       | T32                     |
| 5                       | T43                     |
| 6                       | T46                     |
| 7                       | T49                     |
| 8                       | T51                     |
| 9                       | T41                     |
| 10                      | T56                     |
| 11                      | T64                     |
| 12                      | T24                     |
| 13                      | T42                     |
| 14                      | T13                     |
| 15                      | T26                     |
| 16                      | T40                     |
| 17                      | T44                     |
| 18                      | T45                     |
| 19                      | T52                     |
| 20                      | T62                     |
| 21                      | T67                     |
| 22                      | T29                     |
| 23                      | T35                     |
| 24                      | T36                     |
| 25                      | T48                     |
| 26                      | T59                     |
| 27                      | T70                     |
| 28                      | T28                     |
| 29                      | T38                     |
| 30                      | T47                     |
| 31                      | T58                     |
| 32                      | T68                     |
| 33                      | T34                     |
| 34                      | T63                     |
| 35                      | T65                     |
| 36                      | T33                     |
| 37                      | T61                     |
| 38                      | T3                      |
| 39                      | T27                     |
| 40                      | T37                     |
| 41                      | T55                     |
| 42                      | T69                     |
| 43                      | T21                     |
| 44                      | T30                     |
| 45                      | T53                     |
| 46                      | T54                     |
| 47                      | T18                     |
| 48                      | T20                     |
| 49                      | T6                      |
| 50                      | T16                     |
| 51                      | T22                     |
| 52                      | T23                     |
| 53                      | T31                     |
| 54                      | T9                      |
| 55                      | T14                     |
| 56                      | T17                     |
| 57                      | T10                     |
| 58                      | T19                     |
| 59                      | T7                      |
| 60                      | T50                     |
| 61                      | T4                      |
| 62                      | T8                      |
| 63                      | T15                     |
| 64                      | T25                     |
| 65                      | T39                     |
| 66                      | T66                     |
| 67                      | T12                     |
| 68                      | T60                     |
7. CONCLUSION

During Emergency conditions, prioritization of the network transformers can be done by repair or replacement with social welfare index. By this algorithm, transformers can be easily prioritized and can be implemented in system. This method is implemented in IEEE 342 Node distribution system for providing the prioritization of 68 network transformers during emergency conditions. By this method, system reliability also gets maximized. The transformers which do not have an impact will be considered later.

REFERENCES

[1] Roupchan Hardowar, Serigo Rodriguez, Resk Ebrahim Uosef, Francisco de Leon and Dariusz Czarkowski, “Prioritizing the restoration of network transformers using distribution system loading and reliability indeces”, IEEE Trans. Power Del., vol.32, no.3, jun, 2017.
[2] V. Brandwajn, “ Efficient bounding method for linear contingency analysis”, IEEE Trans. Power Del., vol.3, no.1.pp.38-43, jan.1988
[3] Y.-C. Chang, W.-T. Yang, and C.-C. Liu, “ Improvement on the line outage distribution factor for power system security analysis,” Elect. Power Syst. Res., vol.26, pp. 231-236, 1993.
[4] L.Powell, Power system Load flow Analysis. New York, USA: Mc-Graw-Hill,2005.
[5] T.H.Chen, C.Mo-Shing, K.J.Hwang, P.Kotas and E.A.Chebli, “Distribution system power flow analysis-a rigid approach,” IEEE Trans. Power Del., vol.6, no.3, pp. 1146-1152, jul.1991.
[6] J.L.Carpentier, P.J.DiBono and P.I. Tournebise, “Improved efficient bounding method for DC contingency analysis using reciprocity properties,” IEEE Trans. Power Del., vol.9, no.1, pp.76-84, jan,1994.
[7] G.X.T. Ler,G.Gross, and L. Minghai, “Generalized line outage distribution factors,” IEEE Trans. Power Del., vol.22, no.2, pp.878-881, Apr.2007.
[8] G.Jiachum, F.Yong, L.Zuyi and M.Shahidehpour, “Direct calculation of line outage distribution factor,” IEEE Trans. Power Del., vol.24, no.3, pp.1633-1634, jul.2009.
[9] G.C.Ejebe and B.F.Wollenberg, “Automatic contingency selection,” IEEE Trans. Power App. Syst., vol. PAS-98, no.1, pp.97-109, jan. 1979.
[10] F.D.Galiana, “Bound estimates of the severity of line outages in power system contingency analysis and ranking,” IEEE Trans. Power App. Syst., vol.PAS-103, no.9, pp.76-84, jan.1994.
[11] J. Kang, W. Ma, L. Fu, and F. Ma. “A load flow method using line to line voltages for underground distribution power system,” in Proc 3rd Int. Conf. Elect. Utility Dereg. Restruct. Power Technol., 2008, pp 1205-1210.
[12] M. Ramamoorthy and B.J. Seshaprasad, “An improved method for load flow studies for large power systems,” Proc. Inst. Elect Eng-IERE India, vol.9, pp.93, 1971.
[13] http://sites.ieee.org/pestestfeeders/resources/
[14] Varma, P. S., & Sankar, V. (2011). “Transmission cost allocation with and with out losses in restructured power system.” Paper presented at the 2011 International Conference on Power and Energy Systems, ICPS 2011.
[15] W. H. Kersting, “Distribution System Modeling and Analysis, 2nd Edition”, CRC Press, New York, 2007.
[16] Underground Distribution: Underground Network Systems Practices. EPRI, Palo Alto, CA: 2009. 1019596.
[17] GridLAB-D [Online]. Available: http://gridlab.org