MEDIUM VOLTAGE NETWORK RELIABILITY: EFFICIENCY ORIENTED SUPPLY RESTORATION STRATEGIES

Andreas Theil
Wien Energie Wienstrom GmbH
Vienna, Austria
andreas.theil@wienstrom.at

Gerhard Theil, Marta Theil
Technical University Vienna
Vienna, Austria
gerhard.theil@tuwien.ac.at

Abstract - Efficiency oriented post fault restoration strategies based on object functions such as not supplied energy, customer interruption cost etc. are proposed. The restoration process is conducted by priority ranking of the destinations for fault clearing steps. Application of the presented strategies to medium voltage network reliability evaluation results in a substantial reduction of not supplied energy and interruption cost in comparison to the conventional binary strategy. The method is tested on a real-life distribution network.

Keywords: supply reliability, modeling and simulation, fault management.

1 INTRODUCTION

Network companies are permanently looking for possibilities of operating efficiency increase and cost reduction by structural or operational network modifications. Customer reliability indices such as interruption frequency, interruption duration, not supplied energy and societal interruption cost are dependent on network structure, switching devices, information and protection equipment, the possibility of corrective switching and emergency supply and on post fault management. Interference in one of these scopes may result in deterioration of customer supply reliability. Thus, powerful procedures for the a priori assessment of the influence of network technology and operation modifications on supply reliability constitute essential tools for network management [1].

A large number of publications deals with the problem of network restructuring, whereas the problem of fault management strategy forms rather a marginal topic in most of these papers. However, practical experience gained by reliability assessment for real networks clearly points out that a correct model for post fault management constitutes an essential part of the medium voltage reliability computation procedure. Thus, this paper concentrates on the topic of fault location strategy.

Commercial reliability computation software uses two common strategies for fault location - sequential and binary. In this paper a new approach is presented: Post fault restoration is conducted by real-time priority ranking of the destinations for fault clearing steps. Ranking is based on different object functions such as not supplied load, not supplied energy, customer interruption cost, etc. The network operator can decide for one of these targets, dependent on network state (e.g. time of fault occurrence, load level, consumer types) and operative targets.

The concept is based on the theory of total probability. The object function is formulated as expectation of success corresponding to the chosen destination for a fault clearing step. The new approach was integrated into a computer program for medium voltage network reliability assessment [2]. The program processes independent outages, common mode outages of double lines, station component outages and total station outages. Multiple earth faults are not included. This will be a topic of future research.

Apart from the fault clearing strategy the influence of other features such as network structure or network technology - switches, protection system, fault locators, substation automation system - on system reliability is taken into account as well.

The method can also be applied as an online tool for computer aided post fault service restoration. In the field of network restructuring the method can be used for planning efficient locations of switching points or fault locators.

After description of the basic theory of the method its performance is demonstrated in comparison with the conventional binary fault location strategy for a real-live mixed urban and rural medium voltage network.

2 OBJECT FUNCTIONS FOR POST FAULT SUPPLY RESTORATION PROCEDURES

In medium voltage networks a fault of one of the network components causes the outage of all consumers belonging to the protection area of the feeder. Restoration of supply is performed by repeated sequences of fault location and corrective switching actions (fault clearing steps) executed by the fault clearing crew. The fault location action results in the identification of the "healthy" area and its isolation followed by corrective switching actions for partial customer restoration. In that way the extent of the faulted feeder area is step by step reduced until all customers are supplied and the network component with the fault is found. During this process not supplied feeder load changes continuously with each step.

The choice of the destination for each fault location step determines the reduction of not supplied load and the supply interruption duration of each feeder station. Generally the faulted area contains several stations equipped with switching devices and short circuit detectors. All these stations are potential "destinations" for the fault clearing crew. Thus, before starting a fault clearing step, an analysis of the present network state is performed in order to select the destination promising the best result.

Destination ranking can be done with regard to different criteria depending on the targets for network operation. The following ones are of special interest: restraint of not supplied load, not supplied energy, customer interruption duration, interruption cost, restoration of the major part of not supplied load or of a great number of customers with the least possible delay.

For the r^{th} fault clearing step the "action result AR" for a destination k is evaluated by the statistical expectation $E(AR)_{r,k}$. Its value is a measure for the efficiency dependent on the choice of station k as a destination for the r^{th} step. The values for all possible destinations inside the faulted area V form the discrete object function, equation (1). Its maximum corresponds to the most efficient destination [3].

$$\max \{ \mathbf{E(AR)_r} \} \qquad (1)$$

$$\mathbf{E(AR)_r} = \{ E(AR)_{r,1}, E(AR)_{r,2}, \ldots, E(AR)_{r,k}, \ldots \}_{k \in V}$$

For each station with switching possibility the faulted area can be divided into sub-areas by opening of station switches. The fault is located either in one of these sub-areas or directly in the station. The outage frequency of each area is given by the sum of the outage frequencies of all network components included in it. The fault probability of each sub-area b is proportional to its share of the outage frequency of the total faulted area V, equation (2).

$$p_{r,k,b} = H_{r,k,b} / H_{r,V} \qquad (2)$$

k station in faulted feeder area V (potential crew destination)

r step number

H outage frequencies of all components in the areas V and b.

Assuming that the fault occurs in sub-area b, the supply of the customers located in the areas b' (outside b) can be restored, if corrective switching to a healthy neighbor area is possible. Thus, the expectation of the action result amounts to:

$$E(AR)_{r,k} = \sum_{b \in V} (p_{r,k,b} . \sum_{b' \notin b} (AR_{r,k,b'} . pres_{r,k,b'})) \qquad (3)$$

$AR_{r,k,b'}$ result of actions performed for customers in area b` with regard to a selected criterion

$pres_{r,k,b'}$ probability that the loads in b' can be restored, $pres_{r,k,b'} \in [0;1]$.

The result of a fault clearing step can be evaluated not until after its execution. The step duration $T_{r,k,b'}$ depends on accessibility to the potential crew destination k and on switching possibility during this step (remote controlled or manual). Thus, the duration of the step r can assume values within the range of $[T_{r\,min} ; T_{r\,max}]$. For comparison of effects performed at all possible destinations, the duration $Tc_r > T_{r\,max}$ is assumed accordingly [3].

The best result (highest efficiency) of a fault clearing step will be given if the whole not supplied load L_r is restored with the shortest step duration T_{rmin}. This sets up the reference for the efficiency evaluation. The best possible efficiency results in 1, the worst in 0.

Dependent on the selected criterion, the values of AR are given by:

- degree of not supplied load reduction

$$AR_{r,k,b'} = L_{r,k,b'} / L_r \qquad (4)$$

$L_{r,k,b'}$ not supplied load outside faulted sub-area b

L_r whole not supplied load during the step r.

This criterion does not include the step duration, which means that in the action result (4) neither the accessibility to the destination nor the duration of corrective switching is taken into account.

- degree of not supplied energy reduction

$$AR_{r,k,b'} = [L_{r,k,b'} . (Tc_r - T_{r,kb'})] / [L_r . (Tc_r - T_{r\,min})] \qquad (5)$$

$T_{r,k,b'}$ duration of step r
Tc_r duration for step effect evaluation

- degree of interruption cost reduction

$$AR_{r,k,b'} = \Delta C_{r,k,b'} / \Delta C_r \quad (6)$$

with

$$\Delta C_r = L_r [c_r(t_r + Tc_r) - c_r(t_r + T_{r\,min})]$$
$$\Delta C_{r,k,b'} = L_{r,k,b'} [(c_{r,k,b'} (t_r + Tc_r) - c_{r,k,b'} (t_r + T_{r,k,b'})]$$

t_r starting time of step r
ΔC_r cost increase due to the whole not supplied load from time $t_r + T_{r\,min}$ to $t_r + Tc_r$
$\Delta C_{r,k,b'}$ cost increase due to not supplied load in area b' from time $t_r + T_{r,k,b'}$ to $t_r + Tc_r$
c(t) combined consumer damage cost [4] for the consumer mix of L_r or $L_{r,k,b'}$ at time t

- gradient based values of fastest reduction of not supplied load (7) or of customers number CN (8)

$$AR_{r,k,b'} = [L_{r,k,b'} / T_{r,k,b'}] / [L_r / T_{r\,min}] \quad (7)$$

$$AR_{r,k,b'} = [CN_{r,k,b'} / T_{r,k,b'}] / [CN_r / T_{r\,min}] \quad (8)$$

By repeated applications of this principle for a selected criterion, a tree of steps typical of this criterion is created which sets up the most efficient path to be followed by the crew during service restoration. As a rule these decision-trees are different for different selected criteria.

3 APPLICATION EXAMPLE

The procedure will be illustrated for a simple cable network feeder shown in Fig. 1.

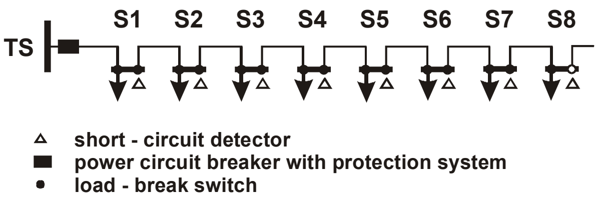

Figure 1: Simple network feeder.

All feeder stations are equipped with load breakers and short-circuit detectors. The feeder is protected by a power circuit breaker in distribution station TS. At the end of the feeder an open load breaker can be manually closed for supply restoration.

Station loads related to feeder load and outage frequencies of station components and feeder sections related to the total feeder outage frequency are shown in Fig. 2. The outage frequencies correspond to faults without known location.

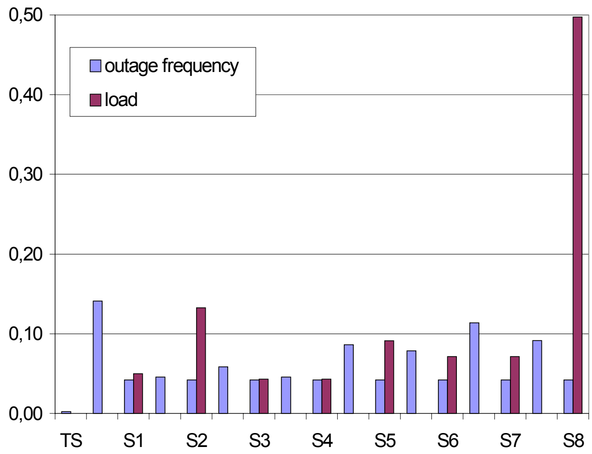

Figure 2: Feeder data.

Fig. 3 shows the partition of the energy consumption of each station to its customer types. These values allow to evaluate the load point combined damage cost (LPCDF) for the stations [4].

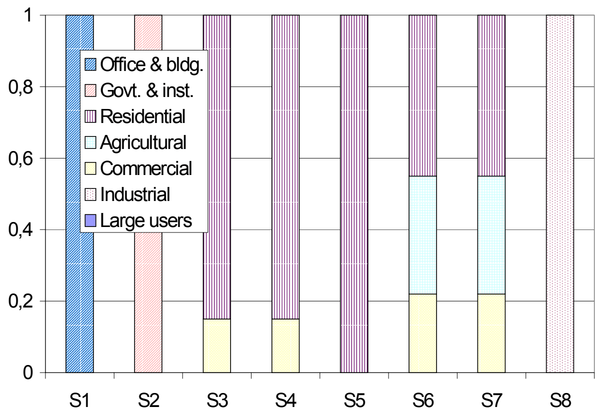

Figure 3: Customer structure.

According to equation (3) the efficiency of fault clearing steps is evaluated for the described targets. Fig. 4 shows the expectations of the reduction degree of not supplied load, not supplied energy and interruption cost for the 1^{th} and the 2^{nd} fault clearing step.

The results show that the most efficient destination path depends on the desired target.

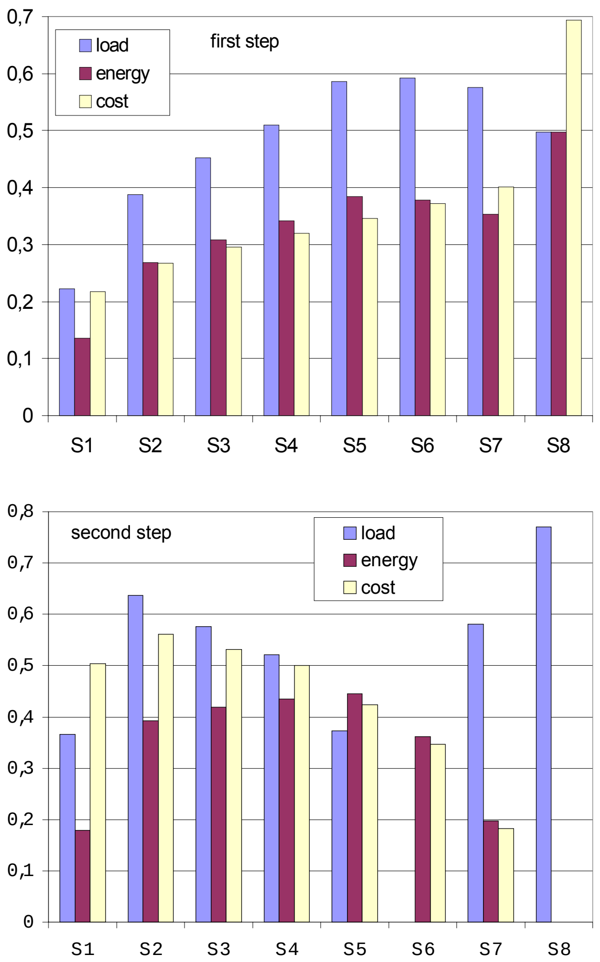

Figure 4: Destination ranking for the first and second fault clearing step.

The binary strategy corresponds to path (S4), (S2 or S6), ... The strategy "not supplied load" proposes the path beginning with (S6), (S2 or S8), see maximal values for "load" in Fig. 4. Strategy "not supplied energy" results in the path (S8), (S6),..., "interruption costs" results in (S8), (S2),...

Fig. 5 shows the reliability indices - not supplied energy and interruption cost - for realizations of the proposed paths (Fig. 4) compared to values for the binary strategy path. Energy and cost oriented strategy turn out to be more efficient than the load oriented strategy for both, not supplied energy and interruption cost. As expected, the energy oriented strategy is most efficient for not supplied energy (8% reduction in comparison to binary strategy results) whereas the cost strategy is most efficient for interruption cost (15% reduction).

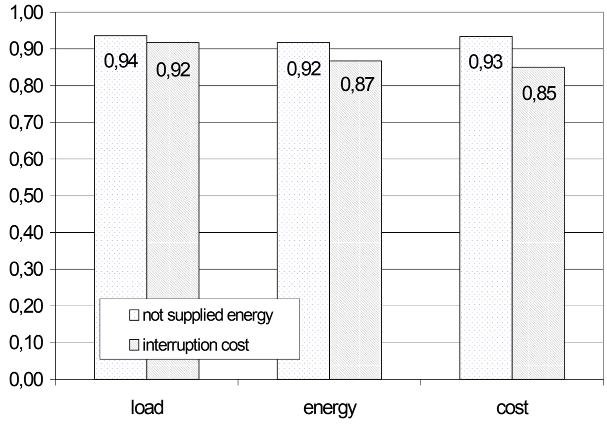

Figure 5: Results of realization of the proposed fault clearing strategies compared to the binary strategy.

4 APPLICATION TO A REAL MEDIUM VOLTAGE DISTRIBUTION NETWORK

The performance of the strategies will be demonstrated for a real-life mixed urban and rural medium voltage network. The network consists of 5 lines (feeders) and is operated as a radial system with open load breakers between the feeders, see Fig. 6.

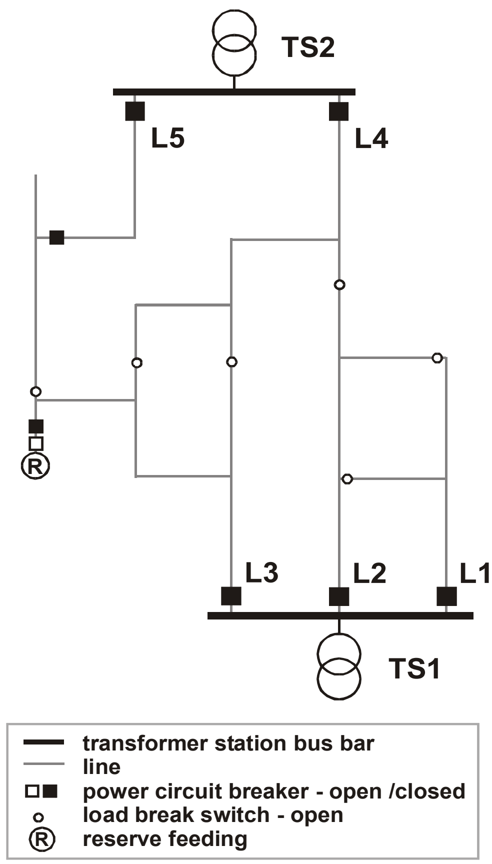

Figure 6: Real-life medium voltage network structure.

Lines L1 and L2 supply the urban, the other the rural areas. Line L4 is a cable system, the other lines are a mix of cable and overhead line sections. The overhead line part of L5 is protected by a power circuit breaker. It has a dead-end branch without possibility of corrective switching. The last station of L3 is equipped with a remote controlled breaker for fast corrective supply restoration. The network supplies about 100 stations with 10 different typical customer structures. It consists of 38 km cable and 17 km overhead lines.

Figures 7 and 8 show a comparison between the results of reliability analysis based on the binary strategy and the efficiency oriented strategies. The not supplied energy resulting from application of the binary and the energy oriented strategy is shown in Fig. 7, the interruption cost for the binary and the cost oriented strategy in Fig. 8.

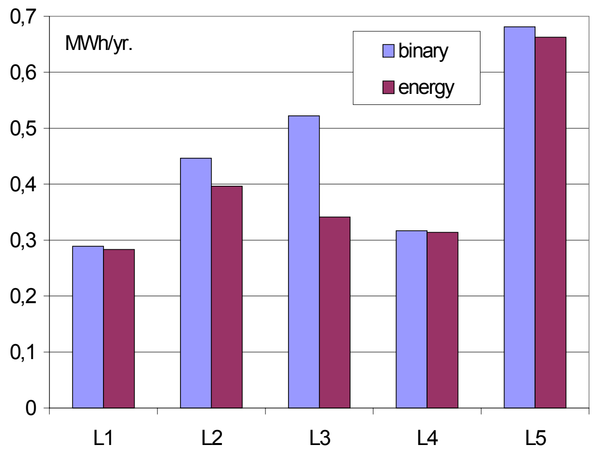

Figure 7: Comparison of not supplied energy resulting from binary and energy oriented fault clearing strategies.

By application of the efficiency oriented strategies not supplied energy and interruption cost are reduced with respect to application of the binary strategy. The difference depends on the degree of the dispersion of station loads, consumer structures and line section length and on factors as fault restoration possibility, network technology, etc. The expected gain for application of the efficiency oriented strategies is proportional to the dispersion of these line parameters and thus different for every line.

An example for a line with low gain expectation is L4: The line consists solely of cables, the line sections between the stations are of similar lengths, the loads are even distributed and composed of similar consumer types. Feeder L3 is an example for a large-gain system: It is a mixed cable and overhead line system. A few stations with large load and sensitive consumers are situated at the line end. Line L5 forms a special case: Due to the dead-end branch without corrective switching possibility the efficiency gain is “masked” by the large amount of not supplied energy.

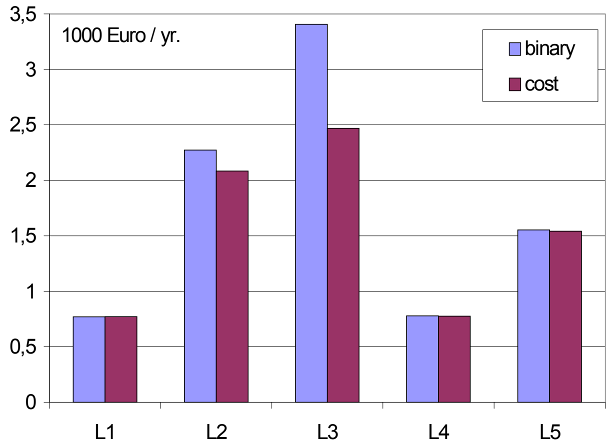

Figure 8: Comparison of interruption cost resulting from binary and cost oriented fault clearing strategies.

For the entire examined network the reduction of not supplied energy is 11,5% for fault clearing by the energy oriented strategy, the reduction of interruption costs amounts to 14,1% for fault clearing by the cost oriented strategy.

5 CONCLUSION

Efficiency oriented post fault restoration strategies are based on object functions such as not supplied load, not supplied energy, customer interruption cost, etc. The restoration process is conducted by priority ranking of the destinations for fault clearing steps. The result is a path of destinations for the activities to be performed by the fault clearing crew. Application of the presented strategies results in a substantial reduction of not supplied energy and interruption cost in comparison to the conventional binary strategy.

The strategies can be applied for:

- A priori planning of fault clearing activities.
- Planning of network restructuring with regard to favorable location of switching points and short-circuit detectors.
- Conducting the on-line fault clearing process under consideration of the actual load situation.

Modification of the fault clearing process is a possible measure to improve system reliability without additional cost expenditure.

REFERENCES

[1] S. Rollauffs, "Aufwand- und Nutzenbewertung einer rechnergeführten Störungsbeseitigung in Mittelspannungsnetzen", Dissertation, Aachen 2003.

[2] G. Theil, M. Theil, "Reliability assessment of medium voltage networks with simulation of the restoration process", 14th PSCC Proceedings, pp, June 2002

[3] A. Theil, "A new method for the network operator to lower the customer damage cost and to improve the load point related reliability indices by the use of optimal supply restoration strategies during outages.", dissertation, TU Graz, 2005.

[4] R. Billinton, S. Ali, G. Wacker, "Rural distribution system reliability worth evaluation using individual customer outage cost characteristics", Electrical Power and Energy Systems 26, 2004, pp 235-240