MEĐUNARODNO REGIONALNO SAVETOVANJE O ELEKTRODISTRIBUTIVNIM MREŽAMA

REGIONAL CONFERENCE AND EXHIBITION ON ELECTRICITY DISTRIBUTION

Crna Gora, Herceg Novi, 5 - 8. oktobar 2004. / ***Montenegro, Herceg Novi, October 5 - 8, 2004***

OPTIMAL NUMBER OF SPARE MV/LV TRANSFORMER UNITS

I. Vlajić-Naumovska, College of Electrical Engineering in Belgrade, Serbia and Montenegro

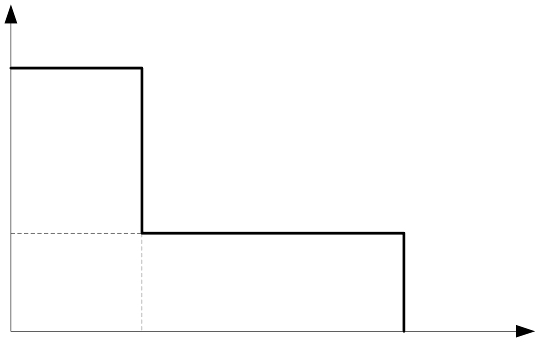
INTRODUCTION

Reliability of power supply of consumers mostly depends on the reliability of the medium-voltage distribution network. The most frequent breakdowns are in lines, which is solved by conceptions of the medium-voltage distribution network, where spare supply is provided in the case of breakdown in any of the line sections (safety criterion “n-1”).
However, in case of MV/LV transformers breakdown, spare supply is not possible, as it is uneconomical to keep an n+1 transformer in a substation. The time required for restoring the function of MV/LV transformers is determined by the breakdown type and decision of the power distribution utility in which way, by repair or replacement, to eliminate the breakdown consequences. If there are spare transformers, the time duration of supply interruptions is shorter and the interruption costs are reduced, but the investment costs are increased. .
The estimated costs used in the existing literature are based on polls conducted among consumers and analyses of certain emergency situations. In analyses of damages due to supply interruptions, an implicit assumption was made that the interruption had occured during the working hours of the consumers, when the damages are the greatest. The paper develops the damage estimate method, including a two-level demand diagram which takes into account the overlapping probability of moment of supply interruption occurrence with the consumers’ working hours.
The possible number of spare transformers is selected along with an analysis of the reliability and corresponding costs. The paper gives an analysis of the model of total costs and average unavailability of a group of MV/LV transformers in the distribution network from a number of spare transformers.

DEPENDENCE OF DAMAGES ON THE THE MOMENT OF SUPPLY INTERRUPTION OCCURRENCE

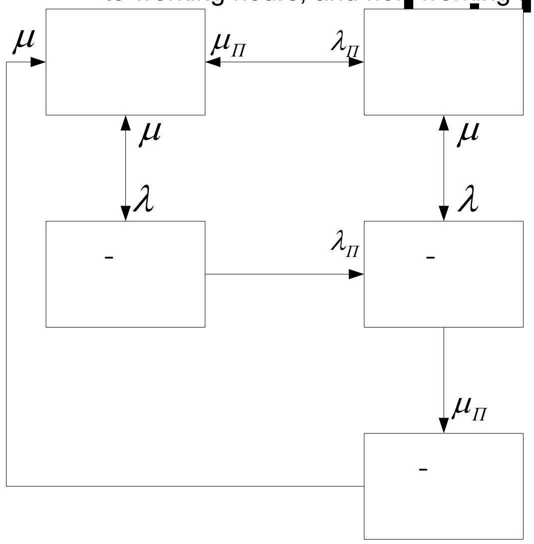
For commercial dealings or the industrial type of consumers, two events are possible: that breakdown occurs during the working hours or during non-working hours. The damage costs in these two cases differ, for if a breakdown occurs during working hours (particularly pertaining to some industrial branches), all that has not reached up to that moment the final processing phase in the production cycle, may be considered as waste.
In Figure 1, is given a simplified diagram of the industrial consumer’s consumption, where consumption during 8 h of working hours is P_m, and the consumption during the non-working hours is P_o.

Figure 1 - Simplified daily consumption diagram of industrial workers consumption



The model for damage estimate of interrupted supply effecting consumers, which takes into account random overlapping of the time duration of repair or replacement of transformer and the working hours of consumers is shown in Figure 2.

Figure 2 - Diagram of transition for industrial type of consumer in case of superposition of breakdown to working hours, and non-working hours respectively.



States 1 and 2 present correct work of consumers depending on the current shift (working or non-working hours). During interrupted supply, transition is made from state 1 to state 3, thereby showing the occurrence of interrupted supply during working hours of consumers, and from state 2 to 4 respectively, thereby presenting the occurrence of interrupted supply during non-working hours of consumers. If the interruption duration is 48h, which is in fact considered to be typical in replacement of MV/LV transformers, the fault shall not be eliminated in the course of one shift, which is marked by transition from state 3 to state 4, and from state 4 to state 5, respectively. State 5 presents the beginning of a new work shift when the consumer could work, but it is not possible because there is no supply. It differs from state 3 (whent the work shift is underway, and interruption of supply occurs), as the consumer is informed about the interruption (there is no iwaste, nor wasted material).

State probabilities for an observed system are computed by solution of Kolmogor's differential equations, derived from the diagram of transitions. Equations for determination of stationary values of state probabilities for the observed system are as follows:

$$\begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ \lambda_{\Pi} & -(\mu_{\Pi}+\lambda) & 0 & \mu & 0 \\ \lambda & 0 & -(\mu+\lambda_{\Pi}) & 0 & 0 \\ 0 & \lambda & \lambda_{\Pi} & -(\mu+\mu_{\Pi}) & 0 \\ 0 & 0 & 0 & \mu_{\Pi} & -\mu \end{bmatrix} \cdot \begin{bmatrix} p_1 \\ p_2 \\ p_3 \\ p_4 \\ p_5 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \qquad (1)$$

For MV/LV transformers, the assumed intensity of outages is λ=0,018. The time required for restoring the function of an observed consumer, after breakdown of MV/LV transformer, is determined by the time of replacement or repair of faulty element.

A spare element is considered to exist and that replacement of transformer by spare transformer takes 48 h. The stationary indicators of the system states are:

λ=0,018

r=48 h

$$\mu = \frac{1}{r} = \frac{8760}{48}\frac{1}{god} = 182{,}5\frac{1}{god} \qquad (2)$$

$$\lambda_{\Pi} = \frac{1}{d_{rad.vr.}} = \frac{8760}{8}\frac{1}{god} = 1095\frac{1}{god}$$

$$\mu_{\Pi} = \frac{1}{d_{nerad.vr.}} = \frac{8760}{16}\frac{1}{god} = 547{,}5\frac{1}{god}$$

Stationary values of probabilities of the observed system's states based on the upper equations are:

$$p_1 = 0{,}33330516$$
$$p_2 = 0{,}66659622$$
$$p_3 = 0{,}00000469 \qquad (3)$$
$$p_4 = 0{,}00002348$$
$$p_5 = 0{,}00007044$$

It is considered that the average duration of a repair or procurement of a new transformer MV/LV is 480 h. When there is not a spare element the stationary indicators of the system state are:

r'=480 h

$$\mu' = \frac{1}{r'} = \frac{8760}{480}\frac{1}{god} = 18{,}25\frac{1}{god} \qquad (4)$$

The stationary values of state probability for an observed system are calculated by solution of Kolmogorov's equations, which are derived from the same transition diagram and for the average restoration time of 480 h amount:

$$p_1' = 0{,}33301184$$
$$p_2' = 0{,}66600283$$
$$p_3' = 0{,}00000538 \qquad (5)$$
$$p_4' = 0{,}00003161$$
$$p_5' = 0{,}00094833$$

By application of Markov's diagram [1] of transition to possible states the probability and expected time duration of of interrupted supply during and after working hours have been calculated.

Costs due to interrupted supply are calculated from the expressions:

$$C = C_i P_m + C_o P_o = c_i \cdot p_3 \cdot T \cdot P_m + c_0 \cdot p_5 \cdot T \cdot P_o \qquad (6)$$

where we have:

P_m - disconnected power during working hours
P_o - disconnected power during non-working hours
C_i - costs per kW of disconnected power during working hours
C_o - costs per kW of disconnected power during non-working hours
c_i - costs per kW of disconnected power per hour of working time
c_o - costs per kW of disconnected power per hour during non-working time
p_3 - the probability of staying in state 3
p_5 - the probability of staying in state 5

Costs per kW of disconnected power during working hours (for state 3) depend on the industry where the observed consumer is employed and are considerably larger for chemical, oil, food industry, glass treatment, metal treatment, etc.

Breakdown of transformer MV/LV is reflected in the system reliability and it causes costs due to interrupted supply which are in proportion to the length of interruption duration. The assumed duration of replacement of a transformer by a spare one is 48h, and the assumed average duration of a repair or procurement is 480h. The calculation shows that the ratio of damage due to interrupted supply is

approximately proportionate to the ratio of the length of interruption duration, when there is a spare element, compared to the case when it does not exist. The exact ratio of these costs for the industrial type of consumers or commercial business depends on the daily diagram and ratio of the size of damage during working and non-working hours.
For economic analyses in this paper, it will be assumed that damages in the second case are of the order of 10 times larger than in case of replacement by a spare element.

OPTIMAL NUMBER OF SPARE TRANSFORMER UNITS

In [2] is presented a model determining the optimal number of spare transformers by means of which minimum annual costs are achieved. This includes damages due to interrupted supply of consumers, as well as procurement and maintenance costs of transformers. The optimal number of spare transformers is the one by means of which minimum total annual costs are achieved.
The cost function may be approximatelyn shown in the following form:

$$C = \sum_{k=1}^{s} p(k) k c_1 + \sum_{k=s+1}^{\infty} p(k)(k-s) c_2 + s I_a \tag{7}$$

where $p(k)$ presents the probability of k breakdowns of elements of the considered type during the considered period, s is the number of spare elements, c_1 is the damage which occurred due to interrupted operation of elements during the replacement thereof by a spare one, c_2 is damage which occurred due to interruption during repair or subsequent procurement of element, and I_a are annual costs of spare elements.
Probability $p(k)$ is calculated as

$$p(k) = e^{-n\lambda T} \frac{(n\lambda T)^k}{k!} \tag{8}$$

In (8) n signifies the number of elements of the considered type, λ signifies the outage intensity of an element, a T signifies the analyzed time. In the considered case, the mentioned period is one year.
The annual costs of a spare element are equal to:

$$I_a = I \frac{i(1+i)^N}{(1+i)^N - 1} \tag{9}$$

where I signifies the cost of one element, i signifies the annual up-dating rate and N is the technical life of the element expressed in years.
In [3] is developed the model for calculation of the average availability of transformer in case of existence of a different number of spare units. The most favourable number of spare transformers regarding availability is a minimum number by which the desired availability is achieved.
The function of average transformer unavailability may be shown in the following form:

$$U = \frac{1}{Tn} \left[\sum_{k=1}^{s} p(k) k d_1 + \sum_{k=s+1}^{\infty} p(k)(k-s) d_2 \right] \tag{10}$$

where d_1 is the average duration of replacement by a spare element, d_2 is the average duration of repair or subsequent procurement of a new element. The first member in the bracket includes a situation when there is a sufficient number of spare transformers, and the second when the number of faulty transformers exceeds the number of spare transformers.

EXAMPLE OF APPLICATION

The described models are applied for analysis of the Power distribution utility Belgrade (Elektrodistribucija-Beograd), in cases of typical combinations of consumers. For transformers 10kV/0.4kV the following data are adopted: rated capacity 630kVA, total number n = 4013, T = 1 year, intensity of failures of transformers 10kV/0.4kV λ=0,007 kv./year, T = 1 year., cost of a transformer I = 8000 EUR, rate of up-dating i = 0,08. The assumed replacement of a transformer by a spare one takes 48h, and the average duration of repair or subsequent procurement of a new one takes 480h. The assumed damages in the latter case are of the order of 10 times larger than in the case of replacement by a spare element.
In TABLE 1 the given calculation results for several ways of including damage due to interrupted power supply by transformer 10kV/0.4kV.

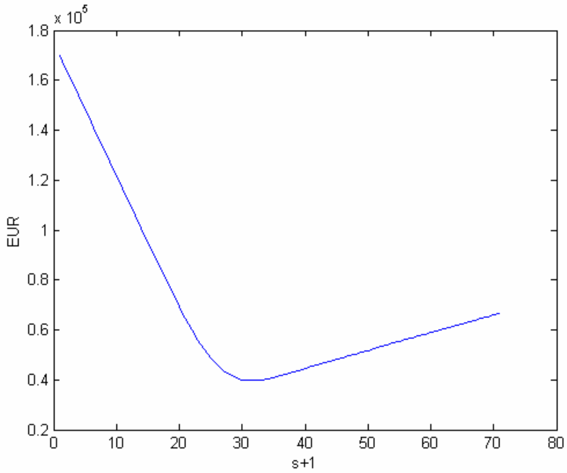
TABLE 1 - RESULTS OF ANALYSIS ON TRANSFORMERS 10KV/0.4KV FOR BELGRADE

No	Damages	c_1, EUR/over	C_{min}, EUR/year	s_{opt}
1	Distribution	604.8	3.97 10^4	31
2	Distribution and 60% domestic households, 30% commercial, 10% industry	25533.9	7.29 10^5	35
3	Distribution and 70% domestic households, 20% commercial, 10% industry	21183.75	6.09 10^5	35
4	Distribution and 75% domestic households, 20% commercial, 5% industry	19953.68	5.75 10^5	35

In the third column of TABLE 1 are shown total annual costs for 4,013 transformers in the case of an optimal number of spare parts s_{opt}.

In Figure 3 is presented the dependence of annual costs for Belgrade on the number of spare transformers (increased by 1) for case 1 of Table 3. If distribution losses due to unsold energy are taken into account, the optimal number of spare transformers is 31. As may be seen, the cost function has an expressed minimum for s_{opt} = 31, which means that even in minor deviations from the optimal number there are considerable increases of annual costs.

Figure 3 - Annual costs for Belgrade, depending on the number of spare transformers



In Figure 4 is given the individual transformer unavailability, depending on the number of spare transformers. The minimum number of spare transformers by which a minimum function of the average transformer unavailability is virtually achieved, is s=35. For a number of spare transformers, which is below the given one, increased values of the average transformer unavailability are obtained. An increased number of spare transformers above 35 virtually does not increase the average transformer availability. The value of average unavailability per transformer for s=35 is U=3.765·10^{-5}. For s = 31 the average unavailability per transformer of U=4.154 10^{-5} is obtained.

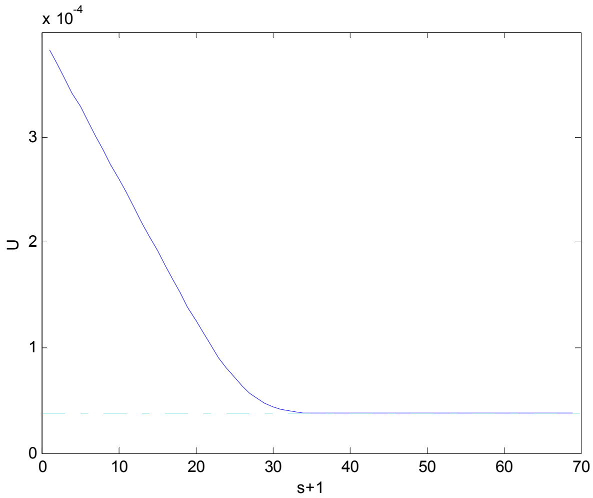


Figure 4 - Average transformer unavailability depending on the number of spare transformers

CONCLUSION

Damages due to interruption are more realistically estimated by means of the model used in the paper, taking into account that these may occur during non-working hours of consumers, that they may be eliminated during non-working hours, or prolonged up to the beginning of working hours.
The paper gives an analysis of the problem of determining the number of spare transformer units for supplying the low-voltage network, in order to preserve the desired reliability of consumer supply, at minimum costs or in order to have, thereby meeting the reliability conditions, the lowest total annual costs.
The models are applied to the urban distribution area. It may be concluded from the obtained results that the cost function has a marked minimum for an optimal number of spare transformers. It is obvious that even in minor deviations from the optimal number, there are considerable increases of annual costs, particularly if there is a smaller number of spare transformers than the optimal number. The number of spare transformers considerably effects the unavailability. It is shown on the considered example how the minimum number of spare transformers virtually providing maximum availability may be determined.

LIST OF REFERENCES

[1] Nahman J.,1992, "Metode analize pouzdanosti elektro-energetskih sistema" ("Metods for power system reliability analizes"), Naučna knjiga, Belgrade, page 35

[2] Nahman J. and others, 1999, "Pouzdanost elektrodistributivnih sistema" ("Distribution system reliability for national power company of Serbia"), research project, Faculty of Electrical Engineering, Belgrade, page 55

[3] Vlajić-Naumovska I., Nahman J., Perić D., 2003, "Optimal number of spare 10kV/0.4kV transformer units with respect to the average transformer availability", ETRAN