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OPTIMAL JOINT SWITCH PLACEMENT BASED ON AGING EFFECT IN DISTRIBUTION NETWORK TO RELIABILITY ENHANCEMENT

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Optimal switch placement in distribution network is usually performed by ignoring the aging effect and assuming a constant failure rate. However, in reality it is possible for the equipment to enter the wear out period. On the other hand, budget inadequacy can be a limitation for replacement of these equipment. What is investigated in this paper is to apply an optimal joint switch placement considering the aging effect of the medium voltage feeders. Furthermore, the joint operation of switches in order to optimally restore the de-energized load points is mathematically modelled to get their outage duration over the fault clearance.

Keywords: aging, reliability, switch placement, distribution network.

1. Introduction

Distribution companies (DisCos) are responsible of giving a reliable service to the customers otherwise they will incur customer dissatisfaction problem. Placement of sectionalizing switches used in this paper is one of the methods employed in distribution sector to increase the reliability level. As an initial works, it is studied in 1991 by [1] using fuzzy logic approach. Afterwards Billinton et al. in [2] have solved the optimal switch placement problem by genetic algorithm concerning different customer damage functions for different type of customers. In [3,4], the distribution network is automated by equipping the system to the automated and remote-controlled sectionalizing switches (RCS) in which the customer outage duration decreases but the capital and maintenance cost of switches increase with the infrastructure cost too.

Also [5] defines the set of manual switches to be upgraded to RCS in a smart distribution system. In [6], manual switches are used as tie switches combined with automatic switches that is cost effective and results in reduction of system energy not supplied (ENS). Solving optimal switch placement problem as a multiobjective optimization in [6,7], it is proposed to minimize the objectives like number of switches, number of customers not supplied or customer interruption cost. Control sequences are also introduced in [8] to have a joint operation of switches (whether manual or automatic) in the network.

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2. Problem definition

Calculating the reliability indices for a distribution system with a least of error is required in order to planning for the budget as better as possible. This issue depends on different cases that one of them is the equipment failure rate. Changes in failure rate includes three periods named infant period, useful period and wear out period. Usually reliability level of system is obtained undergoing the aging effect on the existing components in the network and failure rate is assumed to have a constant value. But the problem is that real size distribution networks contain some components that have entered the wear out period which results in a variable increasing failure rate. If $R(t)$ be the reliability function, $H(t)$ the cumulative failure rate function and $f(t)$ be the probability density function, then the hazard function $h(t)$ is calculated without loss of generality in (1)-(3).

$$H(t) = \int_0^t h(x).dx \quad (1)$$

$$R(t) = \exp(-H(t)) \quad (2)$$

$$h(t) = f(t)/R(t) \quad (3)$$

During the normal life period, the failure density function of component and its cumulative failure distribution can be modeled by exponential distribution function which are characterized by constant failure rate λ and are represented in (4) and (5).

$$f_{\exp}(x) = \lambda.\exp(-\lambda.x); \qquad x \geq 0 \quad (4)$$

$$F(x) = 1 - \exp(-\lambda.x) \quad (5)$$

In contrast with normal life period, there is wear out period involving component aging over time. Several distributions can be used to model the mortality and aging in particular Gompertz [9], Logistic [10], log Logistic [11], loglog [12] and Weibull [13]. Weibull distribution (6) is employed in this paper to best modeling the aging effect.

$$f_{Wbl}(t) = \beta/\eta.(t/\eta)^{\beta-1}.\exp\left(-(t/\eta)^{\beta}\right) \quad (6)$$

Parameter β is shape index and η is the scale index. Based on sampling process of TTF and the TTF method used in [14], the failure rate of aged component as a function of time is calculated through (7)-(11).

$$R(t) = exp\left(-\lambda t^{\beta}\right) \quad (7)$$

$$MTTFF = \int_0^{\infty} exp\left(-\lambda t^{\beta}\right).dt = \Gamma\left(1 + 1/\beta\right)/\kappa = 1/\lambda_0 \quad (8)$$

$$\lambda(t) = \lambda_{eq}\beta t^{\beta-1} \quad (9)$$

$$\lambda_{eq} = \lambda_0^{\beta}\left[\Gamma\left(1+1/\beta\right)\right]^{\beta} \tag{10}$$

$$\Gamma\left(x\right) = \int_0^{\infty} t^{x-1}e^{-t}dt = \left(x-1\right)\Gamma\left(x-1\right) \tag{11}$$

Where MTTFF is the mean time to first failure rate and $\kappa = \lambda^{1/\beta}$. Here β is a parameter denoting the aging effect and λ_0 shows the average failure rate of component irrespective of aging effect. Γ refers to the gamma function so when β is equal to one, λ is independent of time. Equation (10) captures the behavior of failure rate over the time for the aged component. It is extracted by nonhomogeneous poison process (NHPP) and the poison law process too [15,16].

Switch placement

Here the joint operation of manual and automatic types both together is considered. The objective function related to the total cost of optimal joint switch placement problem is taken in (12) which consists of two terms switch cost and cost of energy not supplied (CENS).. Also, as it is shown below, annual load growth rate lg and planning period N_y have serious effect on cost of ENS.

$$\begin{aligned} TCost = &\sum_{f=1}^{N_f}\sum_{s=1}^{N_{s,f}}\left(SC_m X\left(f,s\right)+SC_a.Y\left(f,s\right)\right)+ \\ &\sum_{t=1}^{N_y}\left(\sum_{f=1}^{N_f}\left(\sum_{s=1}^{N_{s,f}}\left(MC_m X\left(f,s\right)+MC_a.Y\left(f,s\right)\right)\right)+CENS\left(t\right)\right)\times PW\left(t\right) \end{aligned} \tag{12}$$

$$CENS\left(t\right) = Loss \times \sum_{f=1}^{N_f}\sum_{i=1}^{N_{c,f}}\left(ENS(f,i,t)\right) \tag{13}$$

$$ENS(f,i,t) = \left(\sum_{s=1}^{N_{s,f}}\lambda\left(f,s,t\right)\times\pi\left(f,i,s,t\right)\right)\times P\left(f,i,t\right) \tag{14}$$

$$PW\left(t\right) = \left[\left(1+inf\_r\right)/\left(1+int\_r\right)\right]^{t} \tag{15}$$

$$\lambda\left(f,s,t\right) = \lambda_0^{\beta_{f,s}}\left(f,s\right)\left[\Gamma\left(1+1/\beta_{f,s}\right)\right]^{\beta_{f,s}}\beta_{f,s}t^{\beta_{f,s}-1} \tag{16}$$

$$P\left(f,i,t\right) = P_b\left(f,i\right)\times\left(1-lg\right)^{t-1} \tag{17}$$

$$Q\left(f,i,t\right) = Q_b\left(f,i\right)\times\left(1-lg\right)^{t-1} \tag{18}$$

Subject to

$$\sum_{f=1}^{N_f}\sum_{s=1}^{N_{s,f}} X(f,s) \le N_{msw} \tag{19}$$

$$\sum_{f=1}^{N_f}\sum_{s=1}^{N_{s,f}} Y(f,s) \le N_{asw} \tag{20}$$

Indices f, s and i respectively denote the feeder number, section number and load point number both in the associated feeder. Also their upper limit is shown by N_f, $N_{s,f}$ and $N_{i,f}$ respectively. Two binary variables $X(f,s)$ and $Y(f,s)$ are introduced which refer to the manual and automatic sectionalizing switch and are 1 if any type of sectionalizing switch is installed in section s of feeder f. Four parameters SC_m, SC_a, MC_m and MC_a are capital cost and annual maintenance cost for both manual and automatic type of sectionalizing switch. The present worth factor is shown by $PW(t)$ depending on two parameter inflation rate (inf_r) and (int_r) due to (15).

CENS is calculated by equation (13) in which a loss value ($Loss$) is defined by DisCo for total unsupplied energy of network. ENS of each customer i on f th feeder is obtained through equation (14). Here the failure rate of s th section on feeder f in year t is shown by $\lambda(f,s,t)$ and the variable $\pi(f,i,s,t)$ stands for outage duration of load point i after fault occurrence on section s of feeder f in year t. But the important point here is the failure rate which due to equation (16) depends on the parameter $\beta_{f,s}$. Equations (17) and (18) refer to the annual load growth. $P(f,i,t)$ and $Q(f,i,t)$ are the active and reactive power of load points and also $P_b(f,i)$ and $Q_b(f,i)$ are their base amount respectively.

3. Switching mechanism and mathematical modeling

A proper mechanism for switching operation has significant impact on reliability assessment, especially in this issue that a joint switch placement is implemented, and it requires its own mechanism. Fig 1 represents a flowchart that gives a general viewpoint from operation of switches by occurrence of a fault.

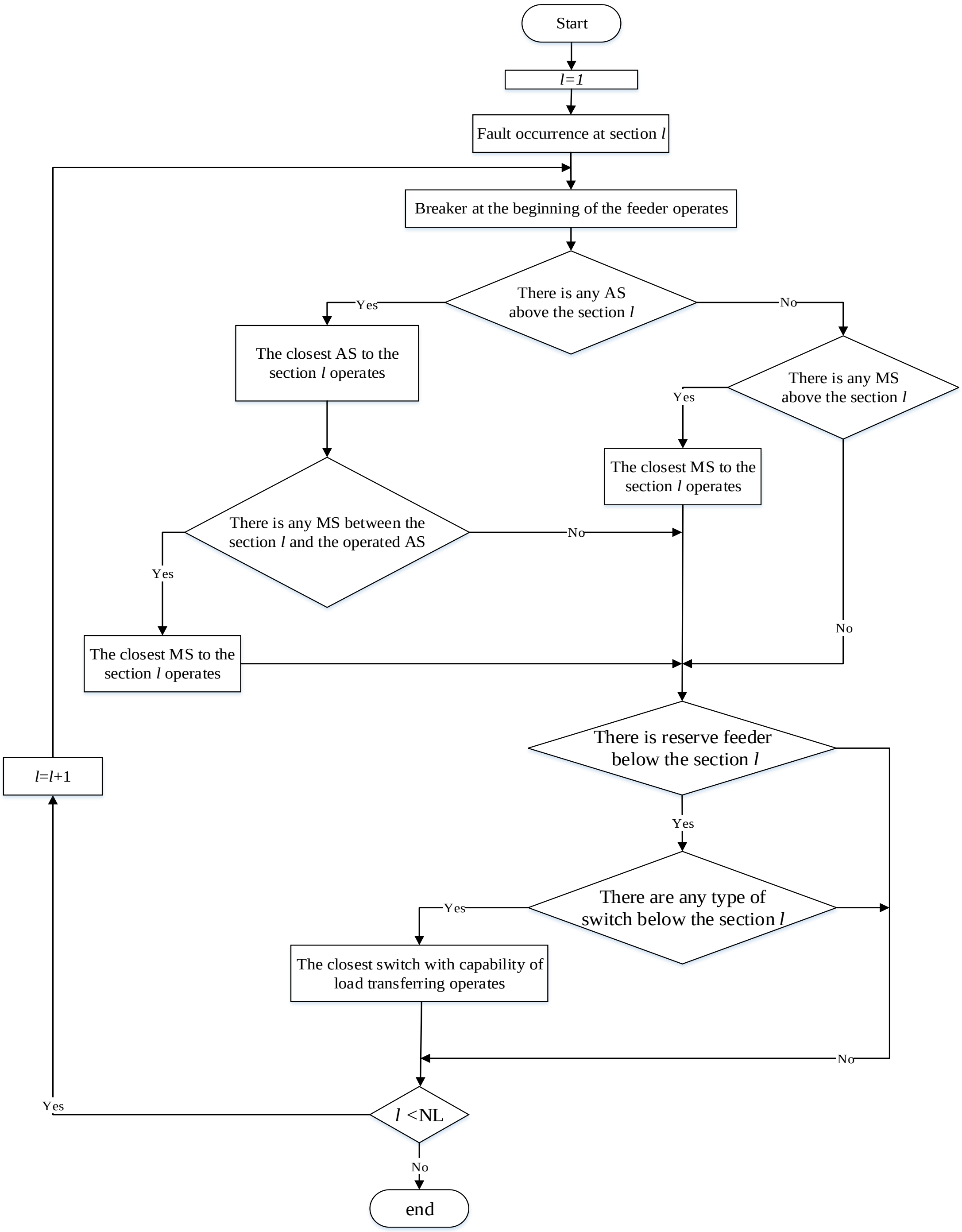

Fig 1- switch operation mechanism flowchart. MS: Manual Switch, AS: Automatic Switch

The abovementioned process in the flowchart can be observed in Fig 2 which represents the procedure on an eleven bus, ten load point feeder.

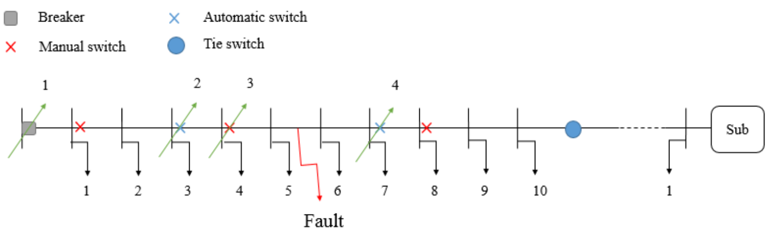

Fig 2. Sequence of switches operation in order to fault isolation and load restoration

This was the complete process for joint operation of manual and automatic switches. Now it is aimed to mathematically model this switching mechanism to facilitate the analysis and better solving the problem. As a matter of fact, the ultimate goal is to achieve the average outage time of each load point effected by failure occurrence in sections ($\pi(f,i,s,t)$) in order to obtain the total ENS of network over the planning period. Before continuing the discussion, a matrix named bus injection to branch current (BIBC) [17] is required for our reliability evaluation. It is a binary matrix that when section s supplies the load point i, its array (s,i) is equal to 1. But one point must be added is that since the section number is equivalent to the load point number connected to its receive node, we can assume the columns of this matrix as the sections of network.

Four binary variable matrices are defined to get the outage duration matrix π that the first one is $\Phi_Y(f,s,i)$. This variable with all of its primary values equal to zero, relates to the load points that are restored by operation of automatic switch above the faulty section s on the feeder f. Therefore, for this section, the indices of these load points are set to 1. Following algorithm explains the formation of this matrix.

$$\begin{aligned}
&for\{f=1:N_f,\ for\{s=1:N_{s,f},\\
&for\{i=1:N_{c,f},\ for\{j=1:N_{s,f},\\
&if\{Y(f,j)=1\ \&\ B(f,j,s)=1\ \&\ B(f.j,i)=0\\
&\Phi_Y(f,s,i)=1\\
&end\}\ end\},\ end\},end\},\ end\}
\end{aligned} \tag{21}$$

For load points above the faulty section that can be restored by operation of manual switch, binary variable $\Phi_X(f,s,i)$ is used. Its formation is same as the $\Phi_Y(f,s,i)$, but with two differences that for $\Phi_X(f,s,i)=1$, it remains zero and instead of $Y(f,j)$, variable $X(f,j)$ must be taken into account.

Another binary variable is $\Psi(f,s,i,t)$, which defines the load points that can be restored via transferring to the adjacent substation by failure occurrence in section s of feeder f in year t. To form this variable the below algorithm in (23) must be followed. Suppose that jth section of feeder f is placed with a sectionalizing switch and it is open. The binary matrix $\mathrm{T}(f,j,t)$ defines that whether the load points below the section j of feeder f in year t cause the overloading of adjacent substation by transferring or not. If it does not cause the adjacent substation to be overload, the related array is 1. Algorithm in (23) shows that how to form the matrix $\mathrm{T}(f,j,t)$ (if there exists a path between this section and an adjacent substation).

$$\begin{aligned}
&for\{ f=1:N_f,\ for\{ s=1:N_{s,f},\\
&for\{ i=1:N_{c,f},\ for\{ j=1:N_{s,f},\\
&if\{ \left(X(f,j)=1 \mid Y(f,j)=1\right) \& \ B(f,s,j)=1 \ \&\ B(f,j,i)=1\\
&for\{ t=1:N_y,\ if\{ \mathrm{T}(f,j,t)=1,\ \Psi(f,s,i,t)=1,\ end\},\ end\}\\
&end\},\ end\},end\},\ end\},end\}
\end{aligned} \tag{22}$$

$$\begin{aligned}
&for\{ t=1:N_y,\ for\{ f=1:N_f,\\
&for\{ s=1:N_{s,f},\ for\{ i=1:N_{c,f},\\
&if\{\\
&\left\{\left(\sum_{i\in f} B(f,s,i).P(f,i,t)+\sum_{f'\in\Omega_{n,f}}\sum_{i\in f'} P(f',i,t)\right)^2+\right.\\
&\left.\left(\sum_{i\in f} B(f,s,i).Q(f,i,t)+\sum_{f'\in\Omega_{n,f}}\sum_{i\in f'} Q(f',i,t)\right)^2\right\}^{1/2} \le K.S_n,\\
&\mathrm{T}(f,s,t)=1,\quad end\}\\
&end\},end\},\ end\},\ end\}
\end{aligned} \tag{23}$$

n is the index of adjacent substation that load points below the section s have the chance to be transferred to it. $\Omega_{n,f}$ is the set of feeders connected to the substation n. In addition, S_n and K are nominal capacity of substation n and its maximum loading percentage respectively. Also for the simplicity of modeling, overloading of feeder through the load transferring is neglected. The last variable is $\Upsilon(f,s,i,t)$ which defines the load points in year t of planning that must remain de-energized till the failure in section s of feeder f is resolved. Building progress for this variable is as follows.

$$\begin{aligned}
&for\{t=1:N_y, \quad for\{f=1:N_f, \\
&for\{s=1:N_{s,f}, \; for\{i=1:N_{c,f}, \\
&if\{\Phi_X(f,s,i)=1 \;\&\; \Phi_Y(f,s,i)=1 \;\&\; \Psi(f,s,i,t)=1 \\
&\Upsilon(f,s,i,t)=1 \\
&end\}, \\
&end\},end\} \\
&end\},end\}
\end{aligned} \tag{24}$$

Now if r_m be the operation time of manual switch (operation time of tie switch too), r_a be the operation time of automatic switch and $r(f,s)$ be repair time section s on feeder f, then $\pi(f,s,i,t)$ is calculated in (25).

$$\begin{aligned}
\pi(f,s,i,t) = \Phi_X(f,s,i).r_m + \Phi_Y(f,s,i).r_a + \\
\Psi(f,s,i,t).r_m + \Upsilon(f,s,i,t).r(f,s)
\end{aligned} \tag{25}$$

Genetic algorithm

Genetic algorithm is an appropriate method to solve the optimization problems like joint switch placement. This algorithm is constructed of three main part named initial population generation, crossover operator and mutation operator that are discussed in [18]. Individuals of any population is called a chromosome that in this problem, the length of each chromosome is equivalent to the number of possible candidate locations to switch placement and these chromosomes are expressed by the string of three numbers 0, 1 and 2 as shown in (26). Zero means that there is not any switch installed in that section. Numbers 1 and 2 are indicator of automatic and manual switch respectively. Then this individual must be encoded to the main solution to be used in fitness function.

$$ch = \{0,0,0,1,2,2,1,...,2\} \tag{26}$$

4. Numerical results

In this section, the comparative results are obtained by running the simulation on a real 95 bus Thailand system [19] depicted in Fig 3 which is large scale enough and suitable for switch placement. All substations are supposed to have a free capacity 30% of its average load in the first year. Planning period is considered to be 15 years. Load growth rate, interest rate and inflation rate are assumed to be 3%, 12% and 9% respectively. The data related to the sectionalizing switches are given in Table 1.

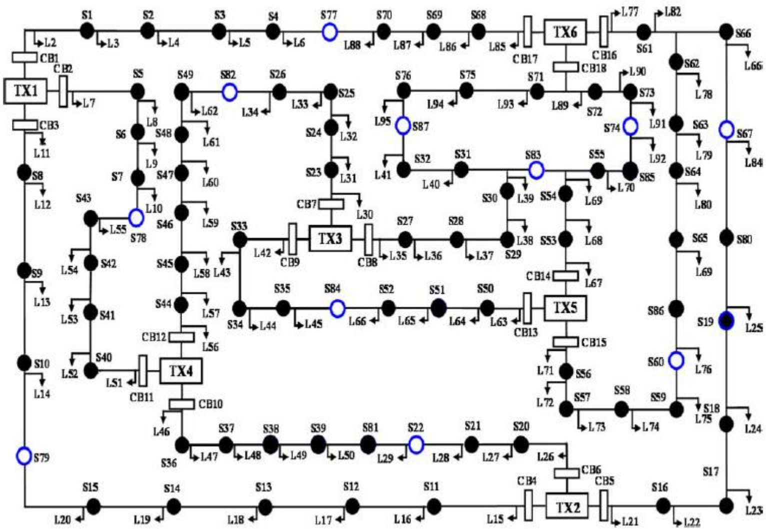

Fig 3- 95 bus network schematic

Table 1

Sectionalizing switch data

Manual switch		Automatic switch	
Capital cost ($)	3000	Capital cost ($)	18000
Maintenance cost	100	Maintenance cost	500
Available number	20	Available number	4

In this paper failures are assumed to be contributed just from the fault occurrence in the feeders. Also, as another assumption the utilized sectionalizing switches in the network have a perfect operation. The problem is solved in two cases. In first one all the sections in the system are in their normal operation mode and in the other case some feeders in the network are in the wear out period.

Case 1:

In the first case all the sections are in the normal life period and because of that their failure rate is assumed to be constant. In the absence of aging effect, total planning cost for the optimal switch placement is 0.744 million $. System ENS amount over the planning period is about 98120 KWh. The result for switch locations are given in Table 2. As it is seen in Table 2, despite the fast restoration capability of automatic switches, its higher cost outweighs the ENS reduction in this case, hence its number is low.

Table 2

Optimal switch locations result in case 1

Manual switch location	2 4 5 12 15 16 18 19 27 30 31 33 44 46 47 49 59 63 64 65 73 79 80 81 83 94
Automatic switch location	3 17 32 48 78 82

Case 2:

A number of feeders in the network have entered the wear out period in case 2. In order to bold the effect of aging in the results, seven feeders $f = \{4,5,6,7,8,9,10\}$ are selected which their failure rate follow Weibull distribution. In this case the considered value for aging parameter β is equal to 2.

Total investment cost is equal to 1.0147 million $ which has considerable increase relative to the cost obtained in previous case. As it was expected, the total system ENS is increased to 135400 KWh. In deed with respect to the aging effect for some feeders, the failure rate dramatically increases in each year and it has negative effect on system ENS. So in this case, number of automatic switches has increased. Table 3 represents the switch locations in the network.

Table 3

Optimal switch locations in case 2

Manual switch location	2 3 5 12 15 18 26 28 30 32 43 44 46 49 59 63 64 65 73 79 80 81 83
Automatic switch location	4 16 17 19 31 33 47 48 78 82

Moreover, the failure rate comparison for these feeders in both cases is represented in Figures 4 and 5 respectively for the mid-year the end year of planning. As it is seen in these Figures, considering the aging effect the failure rate of feeders dramatically increases by going toward the end of planning period. Also Fig 6 demonstrates the behavior of system ENS over the planning period.

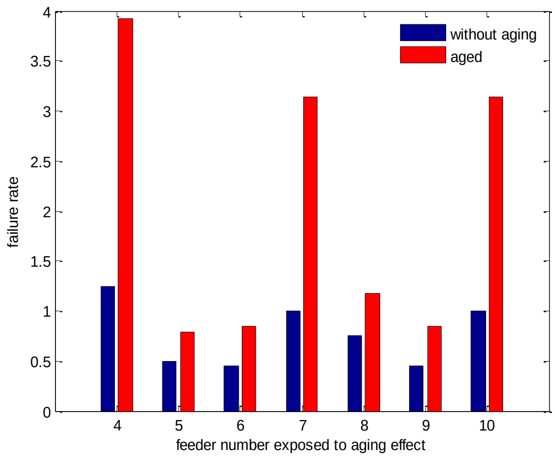

Fig 4- failure rate of feeders in year 8

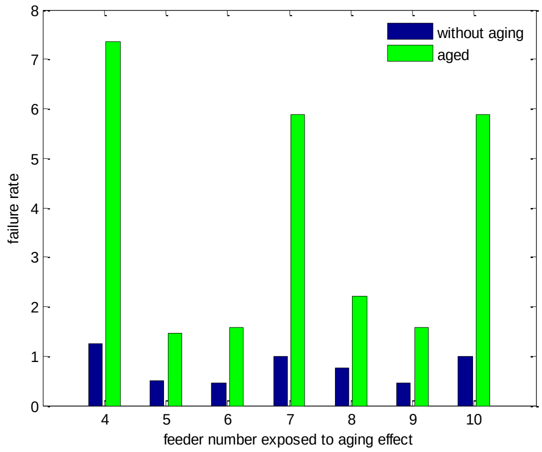

Fig 5- failure rate of feeders in end year of planning

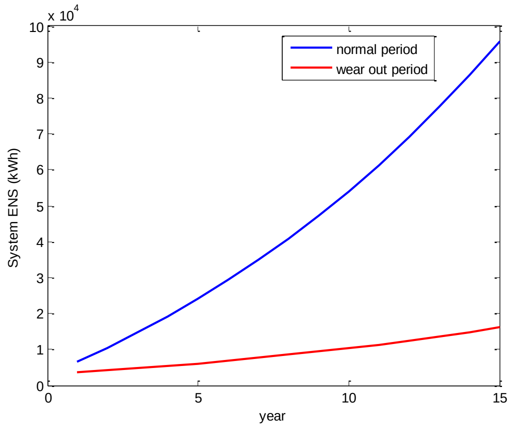

Fig 6- ENS behavior through the planning period and its comparison for the two cases.

5. Conclusion

Switch allocation as an outstanding method in reliability enhancement requires an almost correct and explicit data about failure rate of feeders. One of the main factors which has a dominant impact on failure rate is the aging effect on feeders. By mathematically modeling of joint switch operation, it was shown that in a long-term study, aging exhibits a negative effect on planning cost which relates to the switch and ENS cost. As the aging factor increases, switch cost associated with number and type increases. Also, the ENS of network dramatically goes up. Moreover, despite has higher cost of automatic switch type relative to the manual type, its number had increase due to its fast restoration capability.

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