Abstract - Feeder load balancing and transformer load balancing are used to decrease an overload risk because of the load changing that are happening all the time in the system. So, it is possible to decrease the fault duration and frequency as an overload consequence. The dispatchers usually don’t consider every transformer and feeder with the same importance. Transformer overload usually needs an urgent intervention. The problem becomes more complicated when we deal with 3-phase nonsymmetrical system. It is obvious that load balancing is complicated problem that can be solved by multiple objective decision and compromise.

Keywords: distribution network, load, fuzzy set, membership function, load balancing

1. INTRODUCTION

Besides technical reasons (failure duration and frequency), it is necessary to solve load balancing problem because of economical reasons. It is possible to save the great amount of energy (money) by optimal usage of every element in the system. The main issue is to balance the system, i.e. to form the system in which every transformer and every feeder is loaded equally. It means that load index of each element is equal to the system load index. But, because of the discrentional nature of the load, it is almost impossible to reach the exact value. So, the compromise is necessary. The main idea is presented here.

2. PROBLEM FORMULATION

The suppositions that will be used in this problem solving are:

- every single feeder load is known,
- loads are 3-phase and NONSYMETRICAL,
- loads are presented by constant current value.

The task is to balance the system i.e. to form the system in which every transformer and every feeder will be loaded equally by adequate switching operation. It means that load index of each element should be equal to the system load index. Analogue, each phase has to be loaded equally, which means that phase balancing has to be done, also. Total load and phase load balancing has to be done with a minimum number of switching operations due to switchgear lifetime expectancy. So, three conditions are defined and every condition will be presented using fuzzy sets.

Until this moment lots of statistical methods have been used for load balancing analysis. The results have always been close to the optimal solution. These methods were developed at the end of 80’s by Chinese and Japanese engineers, especially Aoki, Hso, Chen, Kanezashi [5,6,9]. Castro has developed simple exploration technique [8]. He has used databases and current dispatching data. There is also special procedure that deals with load balancing between two transformers (those with the highest and the lowest load). Transformer loads can be almost equalized by correct switcher operation. The same procedure is used for feeder load balancing (loop opening). Baran and Wu have developed gradation load balancing method that is based on the exploration process [7]. Chen and Cho have introduced optimal switching operations based on every hour load samples [10]. Critical switch closing and reclosing is defined by the best sample exploration. These methods deal with separate consideration of transformers and feeders. Lin and Chin [12] also give fuzzy approach to preventive and corrective switching in order to get total load and phase load balance. Roytelman and Shahidehpour analyzed practical aspect of distribution automation [15]. Naga Raj describes fuzzy framework of this issue [16]. He defines target load transfer of every element and describes it by means of membership function.

A fuzzy approach to three different conditions at the same time: total load balancing, phase load balancing, and minimal switchgear lifetime abridgement is presented here.

3. LOAD BALANCING

Basic method steps are:

- definition of the most overloaded element,
- definition of all switching operation that could decrease overload,
- fuzzy set theory usage while choosing the best switching to avoid overload.

System load index is value that describes load in the system according to the following equation:

$$IOS = \frac{\sum_I(T_i)}{\sum_{T_i} \min(I_{\text{naz}}(T_i), SNOF(T_i))}$$ (1)

where

- $I_{\text{naz}}(T_i)$ - nominal transformer load (A)
- $I(T_i)$ - actual transformer load (A)
- $SNOF(T_i)$ - sum of nominal feeder loads connected to transformer $T_i$, (A)
Balanced transformer and feeder load are as follows:

\[ I_{\text{rav}}(T_i) = I_{\text{OS}} \cdot I_{\text{nac}}(T_i) \] \tag{2}
\[ I_{\text{rav}}(f_i) = I_{\text{OS}} \cdot I_{\text{nac}}(f_i) \]

Load balancing method starts with maximal phase current evaluation. It is necessary to divide elements in two groups: donors (elements that decrease load by switching) and acceptors (elements that increase load).

Let’s suppose that single-pole circuit breakers are present in the system. In that case maximal phase load will be:

\[ I_{\text{dav}}(el_i) = \max(I(el_i(a)) - I_{SA}(a) - I_{Sx}(b) - I_{Sx}(c)) \]
\[ I_{\text{prim}}(el_i) = \max(I(el_i(a)) + I_{SA}(a) + I_{Sx}(b) + I_{Sx}(c)) \] \tag{3}

where

- \( I_{\text{dav}} \) - maximal donor load
- \( I_{\text{prim}} \) - maximal acceptor load
- \( I(el_i(a)) \) - actual phase a load of element i
- \( I_{Sx} \) - actual phase load transferred by switching from donor to acceptor

Load balance membership function describes new transformer/feeder load balancing. Every element is described by its own membership function, which defines how close new element load is to its balanced load defined in (2). Analytically, membership function is defined as follows:

\[
\mu_{el_i} = \begin{cases} 
\frac{I(el_i)}{I_{\text{rav}}(el_i)} & \text{for } I(el_i) < I_{\text{rav}}(el_i) \\
1 - \frac{I(el_i) - I_{\text{rav}}(el_i)}{1.21_{\text{nac}}(el_i) - I_{\text{rav}}(el_i)} & \text{for } I_{\text{rav}}(el_i) < I(el_i) < 1.21_{\text{nac}}(el_i) \\
0 & \text{for } 1.21_{\text{nac}}(el_i) < I(el_i) 
\end{cases}
\]

Graphically, membership function is defined in Figure 1.

![Figure 1 Load balance membership function](image)

In that way every element is described by its own membership function. Since, load balancing has to satisfy every single element that is included in load transfer (“AND” element 1, “AND” element 2, …., “AND” element n), logic function “AND” is used. In set theory it is represented as minimum function. According to that, every possible switching operation (load transfer) is described by its own membership function as follows:

\[
\mu_{\text{uravn}(x)} = \min(\mu_{el_1}, \mu_{el_2}, \ldots, \mu_{el_n}) \tag{5}
\]

where

- \( \mu_{\text{uravn}(x)} \) - membership function that describes load transfer by switching x; \( x = 1, \ldots, t \)
- \( t \) - number of possible different load transfers by switching
- \( n \) - total number of element included in load transfer

For final solution it’s possible to choose “OR” switching 1, “OR” switching 2, “OR” switching n. Logic function “OR” is used. In set theory it’s represented by maximum. So, final solution is evaluated with maximal membership function.

\[
\mu_{fi} = \max(\mu_{\text{uravn}(1)}, \mu_{\text{uravn}(2)}, \ldots, \mu_{\text{uravn}(t)}) \tag{6}
\]

Target function can also be defined as sum of relative square deviation:

\[
S = \sum_{i=1}^{N} \left( \frac{I(el_i) - I_{\text{rav}}(el_i)}{I_{\text{rav}}(el_i)} \right)^2 \tag{7}
\]

Balancing process can be safe and improved if it is:

- combined heuristic and fuzzy rules,
- first observed remote controlled circuit breaker,
- transferred load from potential acceptor to neighboring element to get more acceptor’s capacity available, if at first acceptor is not able to accept donor’s load,
- checked protection system after load transfer,
- accepted part of a solution, if whole switching solution is not acceptable.

In some cases it’s not possible to solve the problem because:

- it results with acceptor’s overload,
- available switching doesn’t improve load balancing.

Decreasing of acceptor load, as mentioned above, can solve the first problem. Proposed method analyses only one, the most overloaded element. So, the second problem can be solved by transfer load analysis of all overloaded elements.
4. PHASE LOAD BALANCING

If it’s possible to manipulate every phase load separately (i.e. with single-pole circuit breakers), it is possible to balance phase loads, too. In that case every element that participate in phase load balancing is described as follows:

\[ I_{m}(el_j) = \max(\{I(el_j(a)) - I(el_j(b))\} \cup \{I(el_j(b)) - I(el_j(c))\}) \]  

(8)

where

- \( I_{m}(el_j) \) - maximal phase load difference (A); \( j=1,2,..,n; \)
- \( n \) - total number of elements,
- \( I(el_j) \) - element j phase load (A)

Using those values every single element can be described with phase balance membership function.

\[
\mu_{\text{sim}} = \begin{cases} 
1 - \frac{I_m}{I_B} & 0 \leq I_m \leq I_B \\
0 & I_m \geq I_B 
\end{cases}
\]

(9)

where

- \( \mu_{\text{sim}} \) - phase balance membership function,
- \( I_m \) - maximal phase load difference (A),
- \( I_B \) - base current (A)

Base current (\( I_B \)) defines declivity or severity of phase balance calculation. Usually, nominal thermal current or ground relay current are set as base current. The phase balance membership function is shown in Figure 2.

The same theory used in load balancing procedure is used to choose the most convenient switching for phase balancing. The best solution will be defined by combination of minimum and maximum operators.

Every switching operation is defined with the following membership function:

\[
\mu_{\text{sim}(S_x)} = \min(\mu_{\text{sim}}(el_1), \mu_{\text{sim}}(el_2), ..., \mu_{\text{sim}}(el_n))
\]

(10)

The most convenient switching for phase load balancing is defined as follows:

\[
\mu_{\text{sim}} = \max(\mu_{\text{sim}(S_1)}, \mu_{\text{sim}(S_2)}, ..., \mu_{\text{sim}(S_l)})
\]

(11)

5. INFUENCE OF SWITCHING OPERATIONS

The lifetime of every switching device (switchgear, circuit breaker, switcher…) (SD) is more or less defined with number of switching operation. For every load balancing switching operations are necessary, consequently load balancing has its influence on SD lifetime expectancy. To decrease that influence it is important to define which SDs are the most convenient for that purpose.

In this paper fuzzy set will be used to describe lifetime of SD. Maximum number of switching operations in lifetime is known value (from producer) for every type of device. Dispatchers should know approximate recent working condition of devices in their area. According to that, membership value based on subjective evaluation of life condition is given to every single SD. The membership curve of \( S_x \) device is shown in Figure 3.

\[
\mu_{\text{S_x}} = \begin{cases} 
1 - \frac{\text{NSO} - \text{ZSO}}{\text{ZSO} - \text{TSO}} & 0 \leq \text{NSO} \leq \text{ZSO} \\
0 & \text{NSO} \geq \text{ZSO} 
\end{cases}
\]

(12)

where

- \( \text{NSO} \) - number of switching operation,
- \( \text{ZSO} \) - number of switching operation in lifetime expectancy,
- \( \text{TSO} \) - number of switching operation in lifetime (till this moment).

Membership function for number of switching during analyzed load transfer is defined as follows:

\[
\mu_{\text{S}} = \begin{cases} 
1 & 0 \leq \text{NSO} \leq 2 \\
1 + \frac{\text{NSO} - 2}{2 \cdot \text{MNSO}} & 2 \leq \text{NSO} \leq \text{MNSO}
\end{cases}
\]

(12)

where

- \( \text{MNSO} \) - maximal allowable number of switching operation in actual load transfer,
- \( \text{NSO} \) - number of switching operation in actual load transfer
Every load transfer is realized with at least two switching operations (open/close). Two operations are the most acceptable concerning SD lifetime, so the membership function is equal to 1. More switching operations, lower membership function. If total number of switching operations is higher than allowable (MNSO), membership function is equal to 0.

Procedure described in chapter 3. and 5. is used to get the most convenient switching concerning SD lifetime expectancy and allowable number of switching operations.

\[
\mu_{\text{skl}} = \min(\mu_p, \mu_p(S_x))
\]  
(13)

where

- \(\mu_{\text{skl}}\) - total switching membership value,
- \(\mu_p(S_x)\) - membership value of SD \(S_x\); \(x = 1,2,...,p\)
- \(p\) - number of SD
- \(\mu_p\) - membership value of number of switching for concrete load transfer

Finally, all three conditions (total load balance, phase load balance and number of switching operation) can be observed at the same time using membership functions. That’s very important fuzzy set advantage comparing to the other approaches. Using fuzzy sets it’s possible to represent different conditions with the same type of function. Final solution will be given as minimum of all (three) membership values.

\[
\mu_{\text{skl}} = \min(\mu_{ij}, \mu_{\text{sim}}, \mu_{\text{skl}})
\]  
(14)

Every aspect can be more or less emphasized by the definition of its \(\mu\) function. That’s the other possibility of fuzzy set theory that can be very useful in solving nonsymmetrical load balancing problem.

This approach will be presented on a simple example given in the following chapter.

6. METHOD APPLICATION

In this example nonsymmetrical load balancing is analyzed, taking into account number of switching operation. The distribution network of 10 kV is shown in Figure 5. Load data at the beginning and in the following steps are presented in Figure 6. The procedure used here is presented in chapters above. All three conditions are taken into account. Load index is ratio between actual and nominal load. Phase load balancing is also calculated, as well as influence of number of switching. Table presents total load index. Every step is confirmed by sum of squared deviation value. Obviously, this procedure gives better load allocation concerning load balance and it avoids overload.
7. CONCLUSION

Feeder load balancing and transformer load balancing are used to decrease the overload risk due to load changes. According to that fault frequency and duration are also decreased as an overload consequence. This paper deals with distribution load balancing method based on fuzzy set theory. Thereby transformer load balancing, feeder load balancing and phase balancing are analyzed simultaneously. Switchgear lifetime is defined by number of switching operations. Load balancing should be performed by the minimum number of switching operations. Presented fuzzy set approach is presented on a general example. Figure 6. shows membership values tending to equalize. It proves that the balancing process is successful.

REFERENCES