Control Algorithm of a Smart Grid Device for Optimal Radial Feeder Load Reconfiguration

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***Abstract*—Secondary distribution network, generally speaking, performs as well as the performance of its LV feeders. The main problem a feeder is experiencing is the load unbalancing due to the stochastic nature of its individual single-phase loads: bigger losses in certain phase accompanied with bed voltage regulation and voltage unbalance. The aim of this paper is to address the issue of automatic balancing as progressing from the end of the feeder towards the front using smart device based on three-ways switch selector and artificial intelligence algorithm to minimize the neutral current.**

***Index Terms*— Distribution System, Power Losses, Voltage Regulation, Radial Distribution Feeder, Load Balancing, Smart Device, Automatic Control.**

I. Introduction

The distribution network is an important part of the total electrical supply and its performance should ensure a good quality of supply. It has been reported that approximately 80% of the customers' interruption are due to failure in distribution network. Such performance concerns include overloading of transformers and cables, excessive technical power loss, incorrect load voltage profile, phase voltage and current imbalances. Some of these often produce malfunctioning of protective relays, and poor quality of power delivery to the consumers; very high energy losses 20-40 percentage against international standard of 8-10 percentages [4]. To avoid these, new distribution systems should have means of automatically detect problems in the network and take decisions to provide remedies and optimum performance operation all time at MV and LV levels.

Various methods from the standpoint of feeder loss reduction and load balancing mainly for primary distribution system aiming network reconfiguration have been proposed [1]…[11]. Under normal conditions, load balancing is usually achieved by feeders' reconfiguration and redistributing load currents among feeders and transformers [4], [9], [12], [13]. Recently, some authors proposed the improving performances of distribution system using distributed generation [19]. Even then, this is insufficient; it should be complemented with other techniques ensuring dynamic load balancing along a LV radial feeder.

The classic way for balance a LV radial feeder is trial and error. This involves field measurements and operator judgment. However, due to the inherent dynamic of the loads, this approach works for a limited period of time [14], [17] and service interruption is unavoidable. Hence, the load rearrangement among the phases of the feeder should be subject of automation.

II. Distribution System Prformances

The performances of the distribution system are related with power losses, power flow, voltage regulation and overloading [1], [3], [4], [12], [14].

When reconfiguring the distribution network some objective functions are observed [13], [14], [15].

A. Total Line Losses

Minimizing the system losses is the usually objective of power utility:

$$P_{loss} = \sum_{i=1}^{m} r_i^2 \left(P_i^2 + Q_i^2\right) / V_i^2 \tag{1}$$

B. Total Complex Power Unbalanced

The complex power in a three-phase system is expressed as $\bar{S}_i^j$ ($j = a, b,$ c). The unbalance of these three complex powers can be evaluated as following:

$$\bar{s}_i^{ul} = \sqrt{\left(1/3\right)\sum_{j=a}^{c}\left|\bar{s}_i^j - \bar{s}_i^{id}\right|^2} \tag{2}$$

Where:

$$\bar{s}_i^{id} = \left(1/3\right)\sum_{j=a}^{c}\bar{s}_i^j \tag{3}$$

This is considered for a typical feeder i^{th}. An evaluation of $\bar{S}_i^{ul} = 0$ indicates that the complex power is balanced.

C. Average Voltage Drop

Another important parameter for operating a distribution system is the voltage drop. A good balanced load will reduce the voltage drop. The average voltage drop for a radial feeder can be expressed as:

$$V_d = \left(1/m\right)\sum_{i=1}^{m} VD_i \tag{4}$$

Where m is the number of load points and

$$VD_i = \sum_{j=1}^{m} \left| \left(V_{rated} - V_j^p \right) / V_{rated} \right| \tag{5}$$

With V_{rated} - the rated voltage; V_j^p - the magnitude of the phase voltage at load point i and VD_i - the average of the three phase voltage drop at load point i.

D. Voltage Unbalance Factor

The voltage unbalance factor for a three-phase system is expressed as a function of zero and negative sequence [16]:

$$VUF^0 = \sqrt{(1/m)\sum_{i=1}^{m}\left(V_i^0 / V_i^+\right)} \tag{6}$$

$$VUF^- = \sqrt{(1/m)\sum_{i=1}^{m}\left(V_i^- / V_i^+\right)} \tag{7}$$

III. Proposed Radial Feeder with Smart Device

A. Conventional Radial Feeder

Figure 1 shows a conventional radial feeder where the loads are fairly even distributed along the feeder. When the loads are hard connected the feeder is prone to big unbalances due to the great variation in consumption of each load. Balancing this type of feeder was proposed [14], [17], [18] by using a three-ways selector switch and some artificial intelligent algorithms.

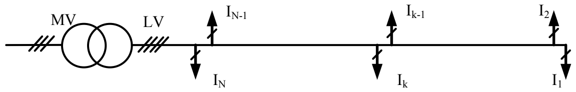

Fig. 1 Classic radial feeder with "distributed" loads

The automation algorithms used in the mentioned works were considering the loads globally and thus the balancing was guaranteed mainly at the feeding transformer. The voltage balancing and power losses along the feeder are not necessarily achieved and thus if the neutral line brakes then a hazardous neutral potential can damage customer appliances.

B. Radial Feeder with Smart Device

Present study proposes a radial feeder with "concentrated" loads (figure 2) connected to the feeder using the same type of three-way switch selector. Figure 3 shows the basic diagram of distribution box (DB) where few load are "concentrated" and connected to the feeder. This smart distribution box can measure the loads current and the three-phase current used by further located loads and is able of deciding via the "control algorithm" on what phase is connected what load. It is generally accepted the fact that power factor of the ordinary users is close to unity and then, further, only the rms value of the current is going to be considered.

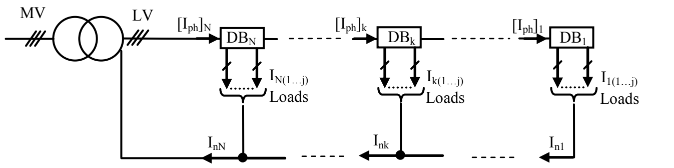

Fig. 2 Radial feeder with "concentrated" loads

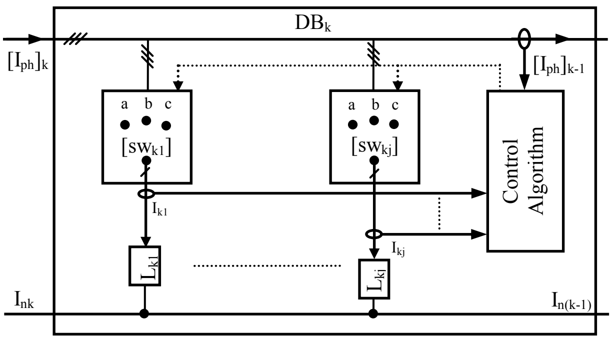

Fig. 3 Distribution box for "concentrated" loads

For this feeder configuration, the power losses ($P_{loss\_k(k-1)}$) could be determined for each sector of the feeder:

$$P_{loss\_k(k-1)} = r_{l\_k} I_{ak}^2 + r_{l\_k} I_{bk}^2 + r_{l\_k} I_{ck}^2 + \left(r_{l\_k}/2\right) I_{nk}^2 \tag{8}$$

with:

$$\underline{I}_{nk} = \underline{I}_{ak} + \underline{I}_{bk} + \underline{I}_{bk} \tag{9}$$

Where r_{l_k} is the resistance of the sector of the line, I_{ak}, I_{bk}, I_{ck} and I_{nk} are the three-phase and neutral currents in the sector. Note that by design the neutral conductor has a double area as phase conductors.
Total power losses in the feeder are:

$$P_{loss} = \sum_{k=1}^{N} r_{l\_k} \left(I_{ak}^2 + I_{bk}^2 + I_{ck}^2 + I_{nk}^2/2 \right) \tag{10}$$

To minimize the power losses, according to (8) and (9) it means minimizing the neutral current which corresponds to have a balanced current system. When the balancing is done in each DB, then neutral current along the feeder is well minimized and thus greatly reducing the effects of broken neutral.

IV. Optimization Algorithm

The current system in the DB_k point of connection can be written as:

$$\left[I_{ph}\right]_k = \left[I_{ph}\right]_{k-1} + \left[sw_k\right]_{3\times j}\left[I_{kj}\right] \tag{11}$$

Where:

$$\left[I_{ph}\right]_k = \left[I_{ak} \quad I_{bk} \quad I_{ck}\right]^T \tag{12}$$

$$\left[I_{ph}\right]_{k-1} = \left[I_{a(k-1)} \quad I_{b(k-1)} \quad I_{c(k-1)}\right]^T \tag{13}$$

$$\left[I_{kj}\right] = \left[I_{k1} \quad \dots \quad I_{kj}\right]^T \tag{14}$$

$$\left[sw\right]_{kj} = \left[\left[sw_{k1}\right] \quad \dots \quad \left[sw_{kj}\right]\right] \tag{15}$$

$$\left[sw_{k1}\right] = \left[a \quad b \quad c\right]^T \tag{16}$$

Where a means the switch sw_{k1} connect the load to phase a and then a = 1 if not connected then a = 0; b means the switch sw_{k1} connect the load to phase b and then b = 1 if not connected then b = 0; c means the switch sw_{k1} connect the load to phase c and then c = 1 if not connected then c = 0. The main constrain for each selector switch is:

$$a + b + c = 1 \tag{17}$$

Even if the power factor is accepted as unity, the neutral current is determined as in complex system:

$$\underline{I}_{nk} = \underline{I}_{ak} + \underline{I}_{bk} + \underline{I}_{bk} \tag{18}$$

A. Optimization Function

Balancing the current system in DB_k it means to have fairly equal currents $I_{ak} \approx I_{bk} \approx I_{ck}$. Then he Least Squares objective function proposed for this study is:

$$J_k = \frac{(I_{ak} - I_{bk})^2 + (I_{bk} - I_{ck})^2 + (I_{ck} - I_{ak})^2}{I_{ak}^2 + I_{bk}^2 + I_{ck}^2} \tag{19}$$

Optimization of this objective function means to minimize it by means of re-arranging the loads through selector switches sw_{kj} and as final result the neutral current is going to be minimized with all the benefits resulting from it.

$$\frac{\partial}{\partial sw_{kj}} J_k\left(I_{ak}, I_{bk}, I_{ck}, sw_{kj}\right) = 0 \tag{20}$$

Apparently the current system follows linear algebra, but the status of switches is binary and eq. (20) needs a combinatorial method of solving. The objective function J_k will be minimized below a threshold value.

B. Optimization Algorithms

The optimization algorithm is based on a heuristic method. Refer to Figure 4 for the flow chart describing the method. The first step is to calculate the ideal balanced phase current, which is the average of the 3 phase currents:

$$I_{Ideal} = \frac{I_{ph_a} + I_{ph_b} + I_{ph_c}}{3}. \tag{21}$$

For each phase calculate whether the phase is overloaded (should release some loads) or under-loaded (should receive some loads). The phases, which should release loads, are then sorted in descending order. This puts the larger loads at the top of the list. This sorting is done in order to minimize the number of loads to be switched to the receiving phases. Starting then with the largest load on the releasing phase, go down the list of loads and check if that particular load may be small enough to fit on the receiving phase (the load should be smaller or the same size as the unbalance on the receiving phase). If the load could be switched over, transfer it to the receiving phase and update the unbalance on the 3 phases. If there is still unbalance, continue this process by checking if the next load on the releasing phase will improve the unbalance on the receiving phase.

Note that there could be different combinations of releasing and receiving phases:

- two receiving phases and one releasing phase,
- one releasing phase and two receiving phases,
- one releasing phase, one receiving phase and one balanced phase.

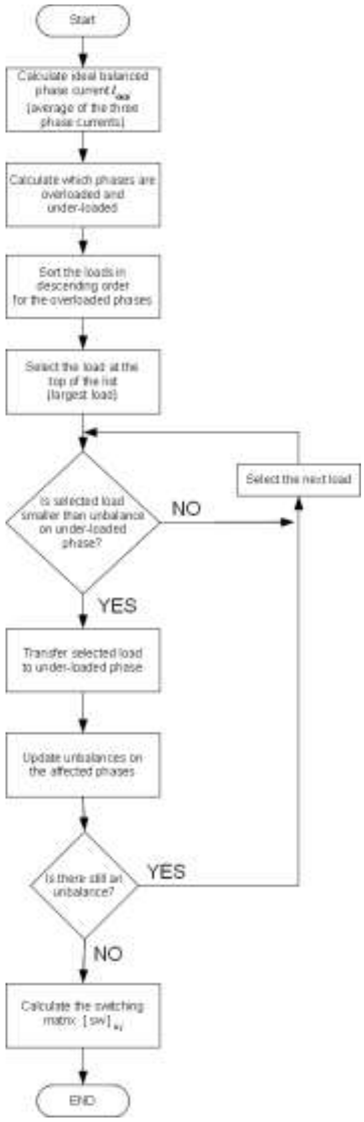

Fig. 4 Heuristic Method Flowchart

C. Operation Mechanism

At turn-on moment switching matrix is chosen just to have an equal number of loads per phase for any point of connection (DB_k). For this study the number of loads per DB is taken as six which means in the moment of system energizing on each phase will be two loads:

$$\left[sw\right]_{kj} = \begin{bmatrix} 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 \end{bmatrix} \tag{22}$$

Once the system is energized; the load currents are determined and sent to the microcontroller performing the control algorithm. It then calculates the objective function J_k ; when the objective function exceeds the threshold the automatic rearrangement start.

V. Practical Results

In order to validate the proposed algorithm, some practical data have been considered. The first application was done for a DB_1 where there is no further current system. Actually, the efficiency of this controller should be done for strongly unbalanced local current systems. Table I shows the optimization algorithm for a random situation at the first point of connection. The results show a big improvement in balancing the system; it should also be noticed that for the far end of the feeder it is not always possible to have a below threshold optimization.

TABLE I. Practical Results for DB_1

$[I]_{(k-1)}$ / $[I]_{kj}$	$I_{a(k-1)}$	$I_{b(k-1)}$	$I_{c(k-1)}$		$I_{a(k-1)}$	$I_{b(k-1)}$	$I_{c(k-1)}$
	0	0	0		0	0	0
31.5	1	0	0	→	1	0	0
16.9	0	1	0	→	0	1	0
5.7	0	0	1	→	0	1	0
8.6	1	0	0	→	0	0	1
7.4	0	1	0	→	0	0	1
1.2	0	0	1	→	0	0	1
$[I]_k$	40.1	24.3	6.8	Optimization	31.5	22.6	17.2
I_{nk}	$28.85\angle -31.68^0$				$12.5\angle -22.1^0$		
J_k	74.4%>10%			→	17%		

The second application was done for the second point of connection (DB_2). For this, the $[I]_{(k-1)}$ was taken from the results from DB_1 after optimization in conjunction with another strong unbalanced $[I]_{kj}$ system. The results are presented in Table II. It can be observed an almost perfect balancing after optimization algorithms rearranged the loads.

To evaluate the performance of the heuristic method, the current unbalance based on the objective function (20) will give an indication about the performance of the method. For different sizes of DB systems (6, 9 and 12 loads per data set), 500 data sets of loads were used for testing the algorithm. This means that there were 500 data sets of the 6-load case, 500 sets of the 9-load case and 500 sets of the 12-load case. These sets of loads were generated automatically to test the load balancing algorithm.

TABLE II. Practical Results for DB_2

$[I]_{(k-1)}$ / $[I]_{kj}$	$I_{a(k-1)}$	$I_{b(k-1)}$	$I_{c(k-1)}$		$I_{a(k-1)}$	$I_{b(k-1)}$	$I_{c(k-1)}$
	31.5	22.6	17.2		31.5	22.6	17.2
29.1	1	0	0	→	0	1	0
0.5	0	1	0	→	0	0	1
6.2	0	0	1	→	0	0	1
18.6	1	0	0	→	1	0	0
7.4	0	1	0	→	0	0	1
18.9	0	0	1	→	0	0	1
$[I]_k$	79.2	30.5	42.3	Optimization	50.1	51.7	50.3
I_{nk}	$43.7\angle 13.5^0$				$1.55\angle -123.2^0$		
J_k	43.1%>10%			→	0.06%		

The results of the test data are shown in Table III. The simulations were done on an iBook G4 1.33 GHz computer. The performance parameters shown are calculated and added together for all of the 500 test data sets. Since 500 test sets were used, the results give a summary of the results obtained from equation (19):

$$J_N = \frac{1}{N}\sum J_k \, , \tag{23}$$

where N is the number of data sets, which in this case is 500. Therefore, we calculate (19) for each data set, and then calculate the average over all 500 data sets.

TABLE III. Performance Results

Parameter	6 Loads	9 Loads	12 Loads
J_N (before balancing)	0.3137	0.2234	0.1633
J_N (after balancing)	0.2215	0.1060	0.0494
CPU Time (s)	0.51	0.61	0.70

The short computation time illustrates the feasibility of implementing the algorithm in real-time. One of the reasons why the algorithm is computationally efficient could be the fact that only simple instructions are used. There are no multiply and divide instructions in the main part of the load sorting routine compared to more sophisticated methods like neural network or support vector machine.

VI. Conclusions

In this paper a novel method for balancing the loads in a radial feeder has been presented. Compared with other similar methods, this achieves a balancing along the feeder and thus minimizing the effects of the neutral line breaking. The numerical algorithm is based on a heuristic method.

The technologies based on static semiconductors with turned-on at zero crossing (for the three-way selector switch), current transducers and microcontroller (for optimization algorithm) for implementations of the proposed solution do exist. These technologies are well proven and their reliability is continuously improving.

The scheme proposed here eliminates the manual reconfiguration of the unbalanced feeders and the running costs.

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