Phase Loading Balancing by Shunt Passive Compensator

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Abstract—This paper presents a proposal to deal with imbalance phase loading phenomenon in power distribution system. Discrete switched passive shunt compensators are considered as the means to help balancing phase loading. Discrete switched passive compensator offers advantages in term of installation cost and simplifies the maintenance process.

A new algorithm is developed to calculate the size of those compensators, this algorithm consists of the unbalance power flow calculation module and discrete optimal sizing module. In addition, the algorithm is written in MATLAB language and tested on actual data of a distribution feeder. All the tests have proven the effectiveness of the proposal and shown the advantages of proposal over others. Moreover, this proposal can be utilized as an useful tool for any electrical utilities.

Index Terms—Discrete Optimization, Distribution System, Imbalance phase loading, Passive Compensator.

I. INTRODUCTION

In power system, voltages (and currents) should be sinusoidal and equal in magnitude, with the individual phases 120° apart. However, the utilities usually experience the imbalance phenomenon in both voltage and current. A major cause of voltage and current imbalances is that loads are not uniformly spread among the three phases. Moreover, other reason may be the asymmetrical distribution feeder impedances possibly caused by incomplete transposition of feeder lines.

The effect of imbalance voltage and current on power system has been well investigated in literature [1], [2]. The unbalanced voltages and currents can result in adverse effects on equipment and on the power system, for example a small unbalance in the phase voltages can cause a disproportionately larger unbalance in the phase currents. Under unbalanced conditions, the power system will incur more losses and heating effects. The effect of voltage unbalance can also be severe on equipment such as induction motors, power electronic converters and adjustable speed drives.

Many mitigation techniques have been developed to deal with imbalance phenomenon in distribution system, generally those solutions can be divided into two categories:

- Rearrange feeders or redistribute the loads in such a way to make the system becomes more balanced [3], [4].
- Install compensators (power quality conditioners) to compensate for any imbalance quantities [5], [6].

This paper focuses on the compensation methods and establishes an appropriate solution in term of capital cost. For imbalance compensation purpose, active compensator such as Static Var Compensator is widely introduced in literature. The power electronic solutions are elegant, but include a greater degree of cost. Cost has been the major factor in limiting the application of power electronic solution over power distribution level. Based on that fact, solutions involving passive components such as capacitor or reactor banks would seem to be the most cost effective solution and these will be investigated in this paper.

Moreover, a new algorithm is developed to calculate the size of compensators. This algorithm includes unbalance power flow calculation module and discrete optimal compensator sizing module. The algorithm is written in MATLAB language and tested on an actual three-phase, three-wire feeder model.

II. PHASE LOAD COMPENSATION PRINCIPLE

Figure 1 shows the general unbalanced three-phase load fed from a three-phase, three-wire source. Load and compensator are connected in delta therefore zero sequence component will equal to zero.

The compensator currents \( (I_{ac}, I_{bc}, I_{ce}) \) is added to load currents \( (I_{a1}, I_{b1}, I_{c1}) \) and then the following equation is satisfied (written for phase A, similarly for phase B and C):

\[
I_a = I_{a1} + I_{ac} = (I_{a11} + I_{a21} + I_{a01}) + (I_{a1c} + I_{a2c} + I_{a0c})
= (I_{a11} + I_{a1c}) + (I_{a21} + I_{a2c}) + (I_{a01} + I_{a0c})
\]  (1)

where \( I_a \) is line current supplying to load after compensation (written for phase A).

The objective of load compensation is to eliminate or limit any the negative and zero sequence components of load currents. Since zero components are zero therefore the line current will become perfectly balanced if the negative sequence component is eliminated. Mathematic expression of
above statement is shown in Eq. 2
\[(I_{a2l} + I_{a2c}) = 0\] (2)

Because \(I_{a2l}\) and \(I_{a2c}\) are complex numbers then equation 2 is equivalent to:
\[
\begin{align*}
\text{real}(I_{a2l}) + \text{real}(I_{a2c}) &= 0 \\
\text{imaginary}(I_{a2l}) + \text{imaginary}(I_{a2c}) &= 0
\end{align*}
\] (3)

The above equations determine the overall conditions for load balancing.

III. PHASE LOAD BALANCING IN DISTRIBUTION SYSTEM

A. Phase load balancing consideration

The implementation of load balancing or load compensation in distribution level may involve some of follow aspects:

Technical aspects: The contribution of this paper is to propose a method that can apply to balance phase loading not only for single load but also for the feeder holding several loads as seen in practice. Other advantage of this method is that it can provide a higher accuracy in calculating size of compensator.

Cost effectiveness aspects: In order to reduce installation cost and make it easier in maintenance then only either pure capacitor bank or pure reactor bank is considered to form the compensator, mixed capacitive and reactive compensator bank is not an option.

Moreover, the discrete switched passive compensator banks (such as discrete capacitor or discrete reactor bank) will be proposed to use as the compensator to further reduce the capital cost.

B. Load balancing algorithm implementation

Considering the representative feeder with several loads as shown in Fig. 2.

The imbalance phase loading does not immediately show its influence over system and equipment due to the fact that thermal inertias of equipment are quite long. Based on that analysis, it is not really imperative to instantly correct the imbalance phase loading situation since it occurs and the balancing action can be carried out on averaged data over a time interval. In details, the unbalance factor averaged over a time interval of 10 minutes to 2 hours interval is recommended in [7].

From above view point, load balancing algorithm is proposed as follow:

Step 1: Determine the first loading level to assess for imbalance estimation.

Step 2: Run three-phase, unbalance power flow calculation for the feeder with the given loading level from step 1. The outputs of this step will be node voltages and load currents (\(V_{Ai}, V_{Bi}, V_{Ci} & I_{abi}, I_{bci}, I_{cai}\)) (here subscript “i” is used to number the loads).

Step 3: Calculate negative current producing by load currents coming from step 2 and the results are assumed to take the following form:
\[\hat{I}_{a2i} = C_i + jD_i\] (4)

with \(C_i\) and \(D_i\) are real and imaginary parts of negative current produced by load number \(i\).

Step 4: Establish equations to determine the compensator negative current which will cancel load negative currents resulting from step 3. Considering the general case, the compensator is three-phase and delta connection as shown in Fig. 3 (here \(Y_{ab}, Y_{bc}, Y_{ca}\) are compensator’s admittances).

Current generated by compensator is:
\[
\begin{align*}
I_{aci} &= (V_{Ai} - V_{Bi})Y_{abi} - (V_{Ci} - V_{Ai})Y_{cai} \\
I_{bci} &= (V_{Bi} - V_{Ci})Y_{bci} - (V_{Ai} - V_{Bi})Y_{abi} \\
I_{eci} &= (V_{Ci} - V_{Ai})Y_{cai} - (V_{Bi} - V_{Ci})Y_{bci}
\end{align*}
\] (5)

In Eq. 5, actual node voltages \(V_{Ai}, V_{Bi}, V_{Ci}\) are used and already known; \(Y_{abi}, Y_{bci}, Y_{cai}\) are unknown variables. Based on Eq. 5, determine the negative current injecting by compensator and final results are as below:
\[\hat{I}_{a2ci} = E_i + jF_i\] (6)

here \(E_i\) and \(F_i\) are real and imaginary parts of negative current required to generate by compensator number \(i\). Note that \(E_i\) and \(F_i\) are functions of variables \(Y_{abi}, Y_{bci}, Y_{cai}\):
\[
\begin{align*}
E_i &= E_i(Y_{abi}, Y_{bci}, Y_{cai}) \\
F_i &= F_i(Y_{abi}, Y_{bci}, Y_{cai})
\end{align*}
\]

Step 5: Load balancing implementation

Load balancing process is to satisfy the balancing conditions as stated in Eq. 3. In detail, the target of this step is to find out the values of variables \(Y_{abi}, Y_{bci}, Y_{cai}\) to fulfill following equation:
\[
\begin{align*}
E_i(Y_{abi}, Y_{bci}, Y_{cai}) + C_i &= 0 \\
F_i(Y_{abi}, Y_{bci}, Y_{cai}) + D_i &= 0
\end{align*}
\] (7)

Because \(Y_{abi}, Y_{bci}, Y_{cai}\) can take only discrete values (as mentioned in Sec. III-A) then the Eq. 7 can not be
solved directly by conventional methods which apply to only continuous variables. That is the reason why the discrete optimization algorithm need to take part in. The objective of discrete optimization will be to ultimately fulfill the Eq. 7 so that minimize the negative current magnitude for each load. Mathematical expression of that objective function can be as below:

$$J = \min \{(E_i + C_i)^2 + (F_i + D_i)^2\}$$  \hspace{1cm} (8)

In this proposal, brute-force search algorithm \[8\] is utilized to solve the discrete optimization. The brute-force search technique is simple to implement and will always find a solution.

Outputs of this step is optimal values of compensators \((Y_{abi}, Y_{bci}, Y_{cai})\) in a discrete manner.

**Step 6**: Add up compensators to corresponding loads and go back to step 2. The iteration will be terminated whenever no further compensation is required.

**Step 7**: Go back step 1 and begin to works with next loading level.

### IV. RESULTS AND DISCUSSIONS

The load balancing algorithm is written in MATLAB and the effectiveness of algorithm is tested with the data coming from an actual feeder which has 3 main lateral loads as shown in Fig. 4.

- All loads have leading power factors.
- The compensators are all inductive due to existing leading power factor of loads; if capacitive compensator is used then the power factor will become worse.
- Compensators are switchable with maximum 10 steps and each step is 25kVAR; 15kVAR and 5 kVAR for compensator 1; compensator 2 and compensator 3 respectively.
- Time interval for unbalance assessment is selected as 2 hours, in other word, each compensator will have 12 time-switching patterns over every 24 hours or a day.

The effectiveness of compensations are illustrated in Fig. 5, 6 and 7. Based on results of negative current before and after compensation, it is clear that the compensation shows a significant load balancing effect, the magnitudes of negative currents that represent the unbalance degree may reduce to less than 1% in some cases. However, the full compensation effect (resulting in zero negative current) can not be expected due to discrete characteristic of compensators.

The switching patterns of compensators are indicated by their tap positions versus time and the results are presented in Fig. 8, 9 and 10.

Moreover, the compensation shows not only load balancing effect but it also helps to reduce power losses through the investigated system. Figure 11 shows power loss improvement after compensation.

In this context, the power losses improvement (PLI) is defined...
V. CONCLUSION

This paper has introduced a cost effective solutions to deal with the problem of phase load imbalance in distribution level. The mechanism of using passive compensator is developed and the algorithm for determining the amount of discrete compensation is presented as well. In addition, compensator’s control strategy to deal with time-varying load patterns is considered and proposed. A simplified case study based on an actual distribution feeder is used to verify the possibility of the proposed compensation strategy. Finally, all the results indicate a feasible, low cost solution applicable to power distribution system.

REFERENCES


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as follow:

$$PLI = \frac{PL_{bf} - PL_{af}}{PL_{bf}} \times 100 \quad(\%)$$

where $PL_{bf}$ and $PL_{af}$ are total power losses before and after compensation.

The possible reasons for power losses improvement can be convinced as follow:

- As stated in Ref. [2], under unbalance loading situation the power system will incurs more losses. Since compensation takes part in, the loading situation approaches to a near balanced status, as a result, the power losses will be smaller.
- Compensators are selected to be all inductive elements and these compensators will help to improve power factors through out the system. Since power factors are improved the power losses will reduce as a consequence.

Based on results of simulation, power losses improvement can be more than 70% and it is about 16% in the least remarkable situation.