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A Practical Way to Balance Single Phase Loads in a Three Phase System at Distribution and Unit Level

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Abstract. The crucial worry in the production of electricity is to be certain that the supplied electricity meets international standards. The growing environmental alerts and the advancement in technology led to the integration of eco-friendly energy sources such as photovoltaic cells and wind turbines to local power grids. Although they provide additional power, the hazardous distribution of these sources in the grid does not benefit power quality measures. This, in addition to the un-linearity in consumption curves, make load balancing at distribution level a must to apply. To achieve the sought balance, load reconfiguration is the solution to be applied. This paper focuses on a practical way that rearranges the loads over the three phases at the unit itself. These changes guarantee electric bills drop and environmental benefits that result from fuel consumption reduction. Practical balancing (PB) is a switching mechanism that guarantees the loads are balanced according to constraints. The main difference between PB and previously proposed techniques such as the Phase commitment (PC) algorithm, The Heuristic (HE) method and the Modified Leap Frog optimization technique is that PB is implementable on real device while others are not. Using the practical balancing algorithm, the percentage of unbalance dropped to 0.38% and 0.43% for the same 15 and 150 loads testing systems used for the phase commitment algorithm. In addition, the average unbalance dropped to 1.6 A and 1.26 A, respectively and the neutral current dropped to 2.08 A and 1.9 A, respectively. The study was conducted on real data for different types of loads.

Keywords. Load Balancing, Optimization, Reconfiguration, Phase Commitment, Practical Balancing Algorithm.

1. Introduction

This paper provides a practical way to balance single phase loads in a three-phase system. The proposed technique has almost the same theoretical results as the PC technique [1], better theoretical results than the HE method [2] and the Modified Leap frog Optimization technique [3]. A three-phase power system is said to be balanced when the three phases have equal voltage magnitudes and equal current magnitudes with a phase shift of 120˚. Asymmetry of transformers, windings and additional energy sources is the main causes of voltage unbalance at the consumer level. In Lebanon, the distribution network is a three-phase plus neutral system (4 wires system), serving the main two types of loads (single phase loads and three phase loads) used in the country. Current unbalance is mostly seen at the low voltage distribution level since it is developed within the unit itself. The main reason for current unbalance at the consumer level is the dissimilar distribution of single-phase loads among the three phases. In electrical installations, at the mapping level, engineers tend to distribute single phase loads almost equally among the three phases while assuming all loads are ON. In practice, rarely all loads are ON and thus the balance is rarely reached. As a result, one or two phases are usually overloaded while the other(s) are less likely loaded. Other common current unbalance factors include overloaded appliances, bad and loose connections, and non-linear and heavy single-phase loads. Phase unbalance reduces service quality; it causes the flow of a heavily distorted current in neutral wires which leads to power losses, heating of power transformers and many more harmful effects [4].

The responsibility of solving unbalance problems lies on both the utility company and the customer who is asked to adopt corrective actions at his house. Most literature stresses on feeders' balancing even though balancing problems start from the facility itself [5]. At the facility level, rudimentary ways are still being used to solve current unbalance problems; electricians tend to change the load distribution manually after many on-site measurements. This primitive manual load reconfiguration causes many service interruptions and thus one disadvantage of this method. Furthermore, the loads' behavior is unpredictable and thus the obtained results are inefficient as they only last for a maximum of few hours [6-7].

With the progress in programming languages and artificial intelligence, different optimization techniques were used to solve the current unbalance problem at the feeder's level. The most famous ones were the Mixed Integer Linear

Programming, Ant Colony Search Method, Simulated Annealing, Single Loop Optimization, Harmony Search Algorithm, Mixed Integer Convex Programming and neural network [8-12]. One efficient method used to solve current unbalance at the facility level was the Phase Commitment algorithm.

The PB algorithm applied in this paper has the same goal as the PC algorithm although its mathematical approach is completely different. Due to its mathematical simplicity, this algorithm can be written and downloaded into a PLC or any professional programmable device that can be integrated in a circutery to insure load balancing. This circuitry is discussed in section III of this paper. The PB algorithm is based on simple Mathematical additions and subtractions (not even matrices) that assign the loads to each phase. Its details are shown in Section IV of this paper. PB's code was simulated using the same real data used to test the PC algorithm. Its results have proven to be almost similar to PC's results although PC uses a much more complicated mathematical approach that makes it almost unimplementable.

2. Standards and Equations

According to NEMA (the National Electrical Manufacturers Association), at the utility level and at no load, the voltage unbalance should not be greater than 3% whereas according to IEEE, it should not go higher than 1% [4]. For the current unbalance, according to IEEE, it is allowed to go six to times higher than the voltage unbalance. The current unbalance percentage can be calculated using the following equation (1) [4].

$$\%\ Unbalance = \frac{(highest\ current - avg.current)}{avg.current} \times 100 \quad (1)$$

Where the average current is the sum of the currents of phase I, phase II, and phase III, divided by 3. In this paper, the current unbalance is not allowed to go higher than 10%.

Another indication of current unbalance is the value of the neutral current. In a perfectly balanced system, the neutral current is equal to 0 A. This indicator can be calculated from symmetrical components according to equations (2) and (3), and making use of parameter a shown in equation (4).

$$\begin{bmatrix} I^0 \\ I^+ \\ I^- \end{bmatrix} = \frac{1}{3} \cdot \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \cdot \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} \quad (2)$$

$$I_n = 3\, I_{ph}^0 \quad (3)$$

$$a = e^{\frac{j2\pi}{3}} \quad (4)$$

In this paper, the neutral current is minimized in all examples.

Another indicator of unbalance is the average unbalance (AU) between phases calculated using equation (5) [13].

$$AU = \frac{|I_{ph1} - I_{ph2}| + |I_{ph2} - I_{ph3}| + |I_{ph3} - I_{ph1}|}{3} \quad (5)$$

When the loads are distributed at any time in a way that guarantees that the percentage current unbalance is less than 10%, the average current unbalance is less than 10 A and the neutral current is minimized, the system is considered to be balanced according to this paper. Load reconfiguration can be translated into an optimization problem constrained by the three conditions mentioned above.

3. Proposed Phase Balancing Model

To ensure phase balancing, a physical model is proposed in this paper. The model is initially divided into two parts: the power connections part and the control connections part. Each of these two parts will be explained clearly in this section. As a general view, the load currents are the PLC inputs. In the PLC, a code runs and gives its commands to a load switch selector that consists of many relays and preferably solid-state relays for fast/on load switching purposes. Fig. 1 gives a general view of the proposed model.

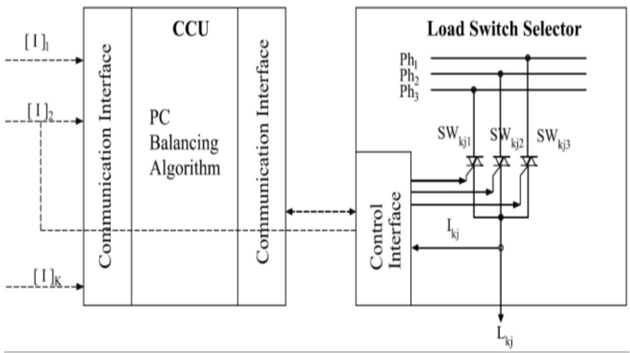

Fig. 1. A General View of the Proposed System

For power connections, each given load has three respective relays. Each of these relays represents a phase. At any time, for each load, one of these relays should be ON and the remaining two should be OFF. For example, if load I is assigned to phase I, the first relay of load I is ON and the remaining two relays of load I corresponding to phase II and III respectively are OFF. The same process applies to all loads. Fig.2 shows the power connections on a three loads scale.

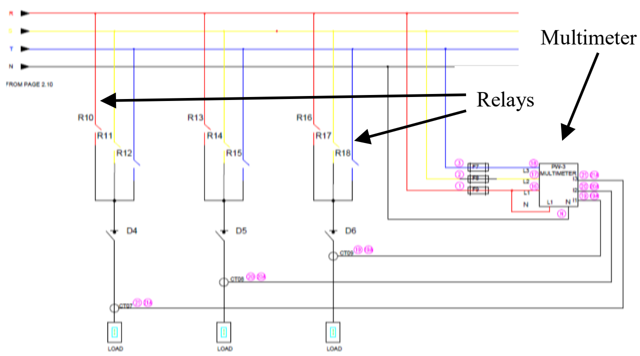

Fig. 2. The Power Connections on a Three Loads Scale

For control connections, the commands are given by a PLC to which is downloaded an algorithm that is explained in detail in section IV of this paper. The used control circuitry works in repeating cycles. The current consumed by each load is attenuated by current transformers. These current transformers pass their respective synonym results to multimeters which by their turn pass these results to the PLC via communication. The PLC outputs are connected to the load relays. After collecting all load currents, the code runs and as a result, each load is assigned to a phase. For example, if for load II, the PLC's control output was 001, this means that load II is assigned to phase III, the third relay of load II is ON and the remaining two relays of load II corresponding to phase I and II respectively are OFF. The process works in cycles because it is repeated after a specific period of time determined specifically based on the case. Fig. 3 represents the proposed control system.

4. Practical Balancing Algorithm

This algorithm is the one downloaded to the PLC. It is based on simple mathematical operations and can be written easily in different programming languages. It does not necessitate additional variables and guarantees approximately similar results as the PC algorithm.

The algorithm first checks the average current unbalance and the current percentage unbalance. If one of these indicators exceeds the limits mentioned in section II of this paper, the data is said to be unbalanced and the code reassigns the loads following a mathematical pattern otherwise the data is balanced and no programming is needed.

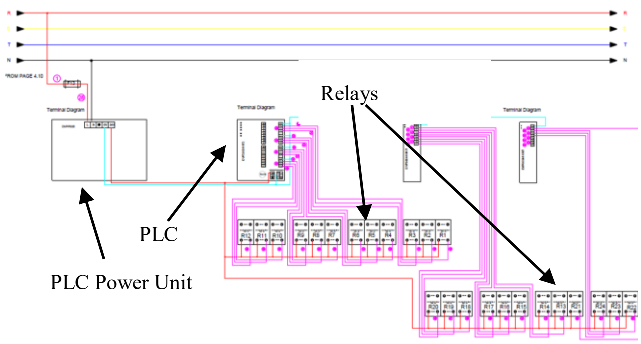

Fig. 3. The Proposed Control System

If the data turned out to be unbalanced, the code gets the average current of the three phases. The ultimate balancing goal is to have approximately the average current on each phase. For this reason, an interval is elaborated within ±0.5% of the average current.

Prior to redistribution, all loads, regardless of the phase each load is assigned to, are put in a data matrix in decreasing current consumption order. These loads are later surfed one by one in the code following this order.

The highest consuming load is directly assigned to phase I and the sum of currents of phase I is elaborated.

Phase I loads are then assigned based on the following condition while surfing the data matrix: If the sum of the currents on phase I is less than the lower bound of the interval or if this sum is greater than the lower bound and less than the upper bound of the interval, the algorithm assigns this specific load to phase I, adds its consumption to the sum of currents on phase I and checks the next load. When the sum of currents on phase I reaches a value within the interval, the code moves to phase II and deletes the loads assigned to phase I from the data matrix.

Now, the highest consuming load in the updated data matrix is assigned directly to phase II and the sum of currents of phase II is elaborated. Phase II loads are assigned based on the same condition mentioned for phase I loads. When the sum of currents on phase II reaches a value within the interval, the code moves to phase III and deletes the loads assigned to phase II from the data matrix. The remaining loads are automatically assigned to phase III. Fig.4 shows the flow chart of the PB algorithm.

5. Simulation and Results

To test the PB algorithm, it is simulated on five real life scenarios. The first consists of 15 loads, the second of 150 loads, the third of 30 loads and the fourth and the fifth consist of 8 loads respectively.

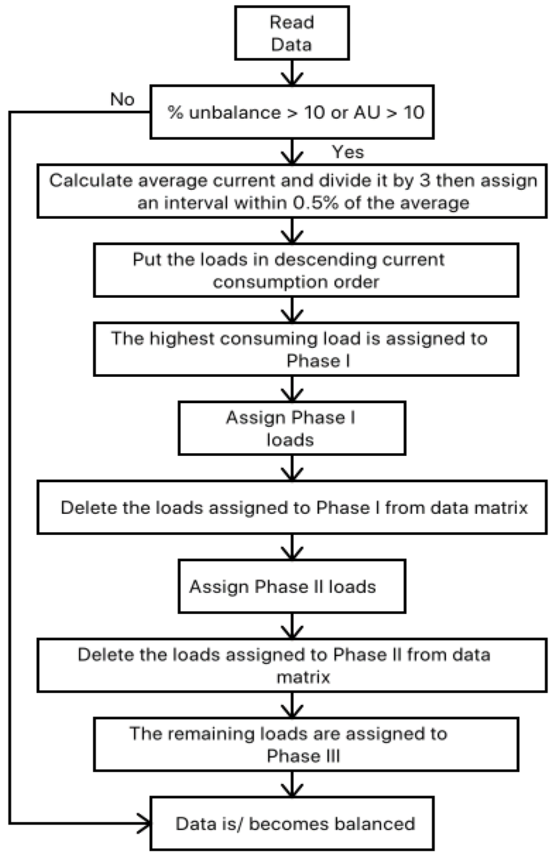

Fig. 4. Practical Balancing Algorithm Flow Chart

The simulation is done on MATLAB 16b, on an 8 GB RAM computer. The simulation's results are compared to previously suggested methods' results. The first set of unbalanced data consists of 15 loads and is simulated for the Heuristic method (HE) [2], the Modified Leap Frog Optimization (MO) [3], the Phase Commitment (PC) algorithm [1] and the PB algorithm proposed in this paper. Results are shown in table I.

TABLE I. 15 LOADS BALANCING RESULTS

	Unbalanced Set	HE	MO	PC	PB
I_{ph1} (A)	321.36	290.8	300	295.05	292.82
I_{ph2} (A)	208.79	299.5	290.8	292.21	295.22
I_{ph3} (A)	352.09	291.9	291.3	294.98	294.20
I_n (A)	130.67	8.2055	8.9605	2.8057	2.08
% Unbalance	19.72	1.843	2.0131	0.3298	0.38
AU	95.53	5.80	6.13	1.89	1.60

Table I proves that for the 15 loads system, the PB algorithm gave the best percentage unbalance, average unbalance, and neutral current compared to other techniques. Its results are almost similar to the PC algorithm. The percentage unbalance dropped from 19.72% to 0.38% (<10%) which means that the percentage unbalance is within standard limits. The average unbalance dropped from 95.53 A to 1.6 A (<10A) which also shows that the average unbalance is within standard limits and the neutral current dropped 65 times from 130.67 A to 2.08 A.

TABLE II. 150 LOADS BALANCING RESULTS

	Unbalanced Set	PC	PB
I_{ph1}(A)	1022.20	609.65	612.14
I_{ph2}(A)	492.38	609.23	612.14
I_{ph3}(A)	313.97	609.65	604.24
I_n (A)	638.00	0.41	1.90
% Unbalance	67.70	0.022	0.43
AU	472.15	0.06	1.26

In Table II, a 150 loads system is simulated. In this case, although the results were close, the PC algorithm showed better results. Both the PB and the PC algorithms' outcomes are within standard limits and thus both techniques insured data balancing.

TABLE III. 30 LOADS BALANCING RESULTS

	Unbalanced Set	PC	PB
I_{ph1} (A)	78.00	55.00	55.00
I_{ph2} (A)	39.00	57.00	55.00
I_{ph3} (A)	49.00	54.00	56.00
I_n (A)	35.08	2.64	1.00
%unbalance	40.96	3.01	1.20
AU	26.00	2.00	0.66

In Table III, a 30 loads system is tested. Results show that the PC and the PB algorithms have almost similar results with a small advantage for PB over PC in this case. All the obtained results are within standard limits.
Tables IV and V show the results for an 8 loads system.

TABLE IV. 8 LOADS SYSTEM I

	Unbalanced Set	PC	PB
I_{ph1} (A)	18.10	13.40	13.50
I_{ph2} (A)	14.00	14.00	14.30
I_{ph3} (A)	10.60	15.30	14.90
I_n (A)	6.50	1.68	1.21
%unbalance	27.16	7.49	4.68
AU	5.00	1.26	0.93

TABLE V. 8 LOADS SYSTEM II

	Unbalanced Set	PC	PB
I_{ph1} (A)	24.80	15.50	14.00
I_{ph2} (A)	7.80	14.40	14.40
I_{ph3} (A)	11.40	14.10	15.60
I_n (A)	15.51	1.27	1.44
%unbalance	69.09	7.49	6.36
AU	11.33	0.93	1.06

Table IV and V show the similarity in the results between the PB and the PC techniques. For system I, PB turned out to be better while for system II, PC results showed a small advantage over PB's results. All outcomes are within limits.

6. Conclusion

Single phase load reconfiguration has proven to solve current unbalance problems. In this paper, the PB algorithm showed its efficiency and its capability to provide the requested balance regardless of the load types and their numbers. Its results proved that PB is better than the Heuristic (HE) method and the Modified Leap Frog Optimization (MO) in balancing single phase loads in a three phase system. The percentage of unbalance using the PB technique dropped to 4.98%, 0.38 %, 0.43 %, and 1.2 % for 8, 15, 150, and 30 loads system respectively. In addition, compared to the PC algorithm, PB has almost the same theoretical results. The major difference between the two techniques lies in the feature that PB can be implemented easily at an affordable price and at the moment, it is being implemented and its experimental results will be ready soon to be presented.

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