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Implementation and Testing of a Practical Product to Balance Single-Phase Loads in a Three-Phase System at the Distribution and Unit Levels

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Abstract. The crucial worry in the production of electricity is to be certain that the quality of the supplied electricity meets requirements. Nowadays, and with the development of technology, there are new energy sources that can add stress to the network such as renewable energy. Being supplied with high electrical quality is a must. One of the basic methods that are recommended to be introduced to the networks is to deal with load balancing at low voltage. Load reconfiguration is one of the best solutions that can be applied to reach balance. The main focus of this paper is to find the optimal consumer load rearrangement at the installation level. These changes are made to maintain the balance between the phases, to reduce the number of electricity bills, and to reduce the fuel consumption that affects the environment negatively. Certain constraints and equations are needed to optimize load distribution. Out of these constraints, an algorithm was made followed by an appropriate switching process to do the automatic balancing. This technique guarantees better results. The proposed process was tested on real data of the different types of loads with different profiles and in every single case, accepted results were obtained.
To sum up, the main goal of this paper is to achieve the balancing of single-phase loads in a three-phase system. To make sure of the theoretical results, implementation was done at the University of Balamand's laboratories using resistive loads and the physical results were always close to the theoretical outcomes.

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

1. Introduction

Load-balancing algorithms are used to distribute power demand among multiple energy sources. They aim to optimize the use of resources and improve system reliability. Some commonly used algorithms include round robin, priority-based, maximum power point tracking (MPPT), adaptive/dynamic load balancing, stochastic optimization-based, fuzzy logic-based, and artificial intelligence-based (AI). Each algorithm has its advantages and disadvantages, and the best algorithm for a given application will depend on factors such as system size, power source availability, and the desired level of reliability.
An active area of research is stochastic optimization in which mathematical optimization techniques such as linear programming and genetic algorithms are used to find the optimal distribution of power demand among sources. Some of the stochastic methods employed are analogous to those employed for resource allocation and balancing for synthetic aperture radars under resource and speckle noise constraints [1]. Another proliferous field of research is AI where machine learning techniques such as neural networks and decision trees are used to optimize power distribution.
This paper shows an implementation of a practical way to balance single-phase loads in a three-phase system. The objective is to implement a prototype that enables to balance single-phase loads in a three-phase system. It mainly focuses on the low residential level but can be generalized to much more complex systems.
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 cause 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 the 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 [2].

The responsibility of solving unbalanced problems lies on both the utility company and the customer who is asked to adopt corrective actions at his house. Most literature stresses feeders' balancing even though balancing problems start from the facility itself [3]. 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. One disadvantage of this method is that this primitive manual load reconfiguration causes many service interruptions. Furthermore, the loads' behavior is unpredictable and thus the obtained results are inefficient as they only last for a maximum of a few hours [4-5].

This is one of the causes of high electricity bills. At this point, this prototype comes into play. It insures that whatever loads are ON, and knowing that three-phase loads are always balanced, we always have a balance between the phases by computations of single-phase loads and as a result, electricity bills will be reduced.

The proposed prototype helps in decreasing power losses, reducing the neutral current in the wires, avoiding equipment heating, and avoiding system degradation and the limitations on the transformer's loading capacity.

This circuitry is discussed in section 3. The PB algorithm is based on simple mathematical additions and subtractions (not even matrices) that assign the loads to each phase [6]. Its details are shown in section 4. The PB's code was simulated using the same real data used to test the PC algorithm. Its results proved to be almost similar to the PC's results although PC uses a much more complicated mathematical approach that makes it almost unimplementable [7]. Finally, implementation and results are shown in section 6.

2. Standards and Equations

According to NEMA (the National Electrical Manufacturers Association), at the utility level and no load, the voltage unbalance should not be greater than 3% whereas according to IEEE, it should not go higher than 1% [2]. According to IEEE, it is allowed to go six to times higher than the voltage unbalance for the current unbalance. The current unbalance percentage can be calculated using the following equation [2]:

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

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) [8]:

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

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.

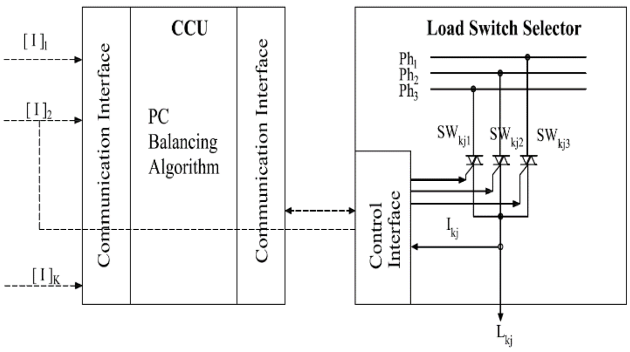

Fig. 1. A General View of the Proposed System

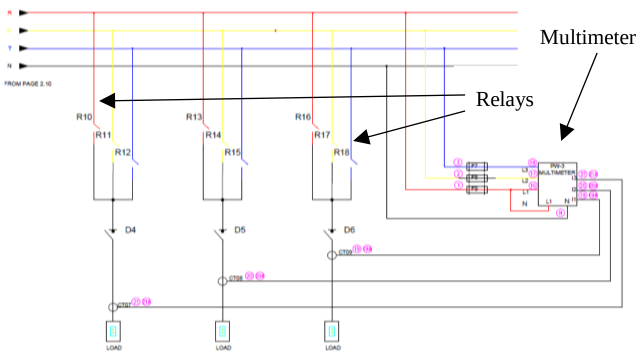

Fig. 2. The Power Connections on a Three Loads Scale

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.
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 in 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 correspond to phase I and II respectively are OFF. The process works in cycles because it is repeated after a specific period 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 [7].
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.

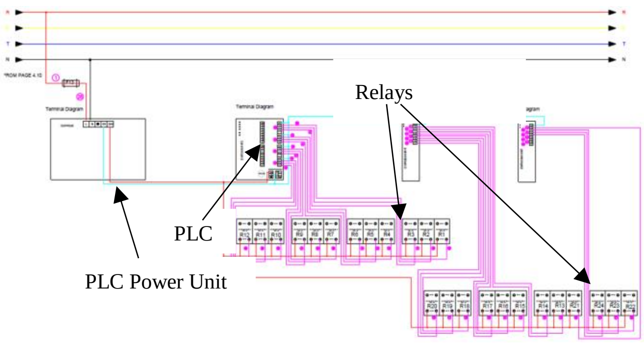

Fig. 3. The Proposed Control System

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.
Before redistribution, all loads, regardless of the phase each load is assigned to, are put in a data matrix in decreasing the 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 in 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 [6].

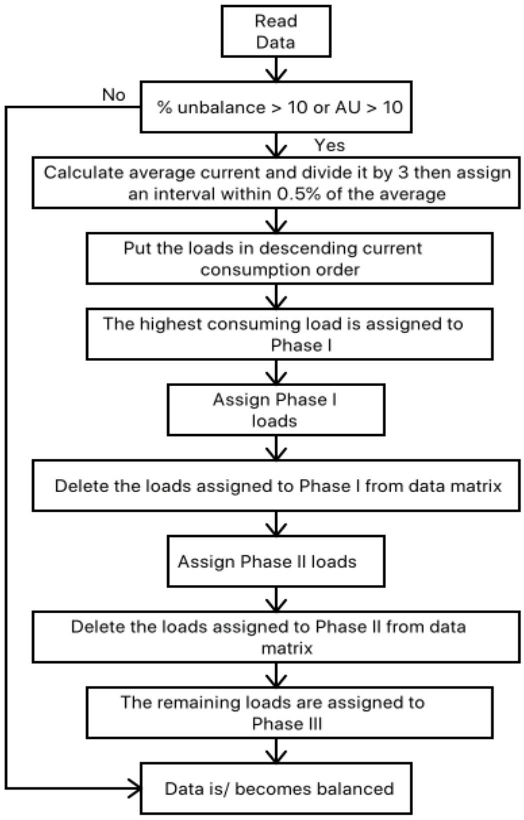

Fig. 4. Practical Balancing Algorithm Flow Chart

The simulation is done on MATLAB 16b, on an 8 GB RAM computer. The simulation's results are compared to the previously suggested methods' results. The PB algorithm showed its efficiency and its capability to provide the requested balance regardless of the load types and their numbers. The proposed technique has almost the same theoretical results as the PC technique [6]. 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 [9-12]. 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 at the moment, it is being implemented and its experimental results will be presented in the next section.

6. Implementation and Results

After the validation of the simulation results, the implementation of the prototype process started.
To change the original load connectivity from one phase to another, the process should be based on using automatic switches. This switching process can be done by different techniques using several devices such as TRIACS, cam switches, and relays. The solid-state relays are used in the paper since there are no moving components in this type and they provide increasing long-lived reliability. In addition, by using SSRs, the switching mechanism can be done without influencing the load: current will not be cut when moving from one phase to another (on-load switching).
A programmable logic controller is a digital computer generally deployed in the industry. It has been mainly adapted for the control of processes like robotic devices, assembly lines, and activities requiring ease of programming, high-reliability control, and fault troubleshooting. A PLC is a real-time system because its outputs are a response to specific input conditions. These outputs must be obtained within a limited time or else unintended and non-desired operations will result. Several PLCs could be used but the most suitable option was the advanced Delta SV2 PLC.
The MATLAB code was transformed into Delta SV2 code using functions that need less execution time than the MATLAB code written before. The same simulation results are obtained, but the execution time is more suitable for the PLC [6].
Concerning the current sensors needed, they are not regular. The data they should give must be analog for it to be an input to the controller so transferring the data read by the sensors to the PLC is also a main difficulty. After research, a functional multimeter that transmits data to the PLC via communication (serial number) was found.
The goal of this work is to sense alternating current inputs and to obtain an analog output that duplicates the wave shape of the sensed current [12].
For every load, a current sensor is required so the number of current sensors needed is equal to the number of loads. In addition, three additional current meters are used to measure the current across the three phases.
A multifunction meter will be used. This device communicates with the PLC via communication (Serial numbers). Each device senses the current of three loads at once.
The implementation process is divided into several steps:

- Cable Trays Placement
- Equipment Placement
- Power Connections
- Control Connections
- Full Product

Fig. 5 shows all the components put together inside the board where:

- D0 represents the main 3-phase circuit breaker
- D1…D8 represent 1-phase circuit breakers
- CT 1…12 represent the current transformers
- R1…24 represent the solid state relays
- F1… & FF represent the 2A fuses.
- DVPPS05 represents the PLC Power Supply
- DVP 28SV11T2 represents the PLC
- DVP08SN11T represents the PLC extensions

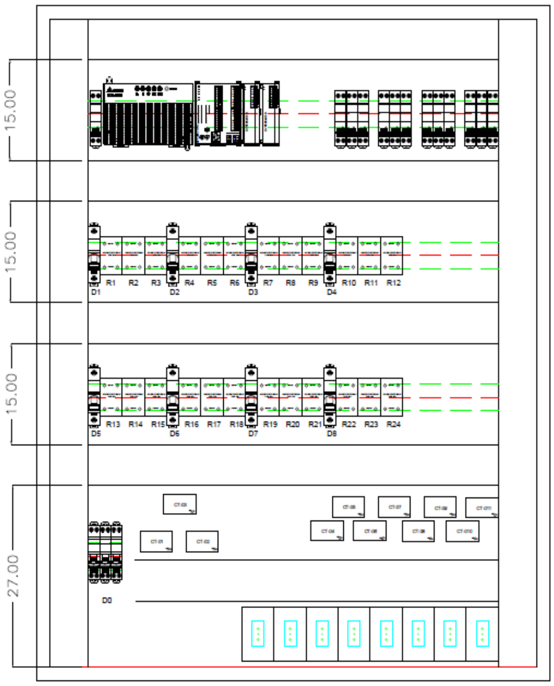

Fig.5 Internal view of the panel board

Fig. 6 shows all the power connections between the components for the first 3 loads.

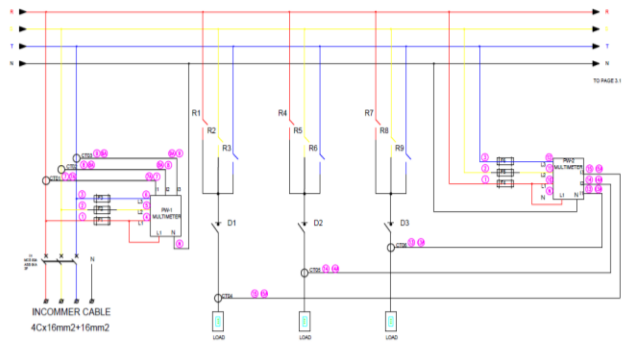

Fig. 6 Power connections for load1, load2, load3

Fig. 7 shows the full product seen from the inside where all needed components are placed and connected.

To verify that the product is working, three testing scenarios were done using 8 different loads consuming each a specific amperage.
The loads were:

- Heater (1) consuming 9.2 A
- Heater (2) consuming 8.3 A
- Heater (3) consuming 7.4 A
- Toaster consuming 6.1 A
- Dryer (1) consuming 4.3 A

- Dryer (2) consuming 3.2 A
- Dryer (3) consuming 2.8 A
- Boiler consuming 1.4 A

It is important to mention that in this part, a 3-phase breaker of 80 A was used so that no interruption will occur in the testing process.
The testing scenarios were:

- All loads are connected to phase I.
- The loads are connected arbitrarily among the phases.
- Removing 1 load from the process at a time

The testing focused on the rearrangement of the loads among the phases and on the number of switches in each scenario.
In this part, the results will be presented and each table will show: the load connection to which phase before and after balancing, the phase current before and after balancing, the number of switches needed to achieve balancing, the average unbalance (AU), and the percentage unbalance.

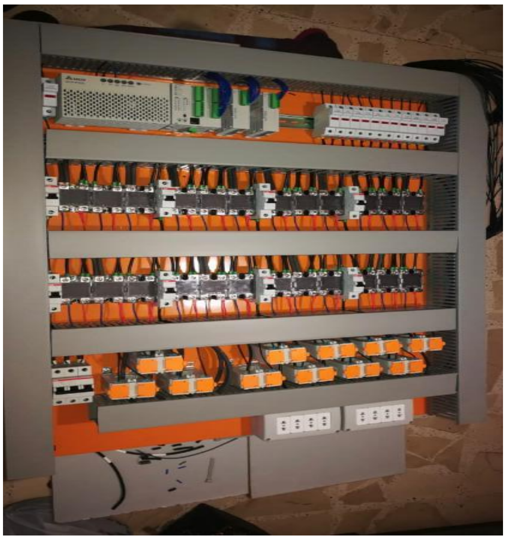

Fig. 7 Full product seen from the inside

A. *All Loads Connected to Phase I*

TABLE I. Scenario 1 results: All Loads connected to Phase I

	Before balancing	After balancing
Load 1 phase (9.2A)	1	1
Load 2 phase (8.3A)	1	2
Load 3 phase (7.4A)	1	3
Load 4 phase (6.1A)	1	2
Load 5 phase (4.3A)	1	1
Load 6 phase (3.2A)	1	3
Load 7 phase (2.8A)	1	3
Load 8 phase (1.4A)	1	3
Phase 1 current	42.7	13.5
Phase 2 current	0	14.4
Phase 3 current	0	14.8
Number of Switches	-	6
AU	42.7	0.86
Percentage unbalance (%)	200	4.05

In this scenario, all loads are connected to phase I. From Table I, it is clear that the switching mechanism is working. The loads are redistributed among the three phases to achieve balancing. The number of switches needed is six, meaning that six loads have changed their phases. The percentage unbalance changed from 200% to 4.05%, which is less than the 10% defined in the standards. The design was able to distribute the loads among the phases in a realistic way.
This example is not realistic; it was only done to prove that the design is functioning.
Real-life examples will be shown in the next parts.

B. *The Loads Are Connected Arbitrarily Among the Phases*

TABLE II. Scenario 2 results: Loads are connected arbitrarily

	Before balancing	After balancing
Load 1 phase (9.2A)	1	1
Load 2 phase (8.3A)	2	2
Load 3 phase (7.4A)	1	3
Load 4 phase (6.1A)	2	2
Load 5 phase (4.3A)	3	1
Load 6 phase (3.2A)	1	3
Load 7 phase (2.8A)	3	3
Load 8 phase (1.4A)	3	3
Phase 1 current	19.8	13.5
Phase 2 current	14.4	14.4
Phase 3 current	8.5	14.8
Number of Switches	-	3
AU	22.6	0.86
Percentage unbalance (%)	39.14	4.05

In this part and to be more realistic, all loads are connected arbitrarily among the three phases. From Table II, it is clear that the switching mechanism is working again. Three switches are needed to achieve balancing. The design was able to distribute the loads among the phases in an adequate way using 3 switches. Table II shows that the load distribution results obtained are similar to the distribution of the previous part. The percentage unbalance changed from 39.14% to 4.05%, which is less than the 10% defined in the standards.
This example illustrates a real-life example where the loads are distributed among the phases with certain unbalance.
In the next part, the balanced results of part '*B*' are used and other changes to the loads will be done, to test the efficiency of the product.

C. *Removing One Load from the System at a Time*

1) Scenario 3.1: Removing Load 8 (1.4 A)

In this part, any load could be removed to check if the prototype will respond and function properly. Load 8 is chosen to be removed. From Table III, it is clear that the percentage unbalanced when removing load 8 is 4.65% which is less than the 10% defined in the standards. The switching mechanism's decision was to do nothing in this case, because the percentage unbalance is less than 10%.
This example illustrates that the product took the correct decision when load 8 was removed.

TABLE III. Scenario 3.1 results: Removing one load from the system at a time

	Before balancing	After balancing
Load 1 phase (9.2A)	1	1

Load 2 phase (8.3A)	2	2
Load 3 phase (7.4A)	3	3
Load 4 phase (6.1A)	2	2
Load 5 phase (4.3A)	1	1
Load 6 phase (3.2A)	3	3
Load 7 phase (2.8A)	3	3
Load 8 phase (1.4A)	-	-
Phase 1 current	13.5	13.5
Phase 2 current	14.4	14.4
Phase 3 current	13.4	13.4
Number of Switches	-	0
AU	0.66	0.66
Percentage unbalance (%)	4.65	4.65

2) Scenario 3.2: Removing Load 4 (6.1 A)

TABLE IV. Scenario 3.2 results: Removing load 4

	Before balancing	After balancing
Load 1 phase (9.2A)	1	1
Load 2 phase (8.3A)	2	2
Load 3 phase (7.4A)	3	3
Load 4 phase (6.1A)	-	-
Load 5 phase (4.3A)	1	2
Load 6 phase (3.2A)	3	1
Load 7 phase (2.8A)	3	3
Load 8 phase (1.4A)	3	3
Phase 1 current	13.5	12.4
Phase 2 current	8.3	12.6
Phase 3 current	14.8	11.6
Number of Switches	-	2
AU	4.33	0.66
Percentage unbalance (%)	21.31	3.27

Another test is done to validate this part. In this part, load 4 is removed. From Table IV, it is clear that the switching mechanism's decision has responded and the loads were distributed properly to insure load balancing. Before balancing, and when removing load 4, the percentage unbalance was 21.31% which is higher than the 10% defined in the standards and thus the switching mechanism will react. Two switches were needed to achieve the balancing again.

After balancing, the percentage unbalance changed from 21.31% to 3.27% which is less than the 10% defined in the standards, and thus the explanation of the product's decision. This example shows that the results obtained are verified and that the prototype is functioning properly when load 4 (6.1 A) was removed.

7. Conclusion

Single-phase load reconfiguration has proven to solve current unbalance problems. The PB algorithm has shown its efficiency and its capability to provide the requested balance regardless of the load types and their numbers. In this paper, the implementation and testing of a prototype to achieve load balancing have been shown. Testing of the full product has been done by considering real-life examples. The results have shown the phase connection of each load before and after balancing. In addition, the phase current was shown before and after balancing. Moreover, the number of switches needed to achieve balancing has been given. Furthermore, the average unbalance and the percentage unbalance have been exposed. All tests done have shown that the percentage unbalance was less than 10% defined in the standards and thus the efficiency of the product's decision.

Possible future work may comprise stochastic-based genetic algorithms and AI-based machine learning techniques for load balancing. The results of such work can also be further extended by simulating them using FPGA simulation software and testing them on FPGA-based digital hardware to observe their effectiveness in a real-life environment.

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References

[1] J. Dubois, "Poisson Modulated Stochastic Model for Partially Developed Multi-Look Speckle," *Proceedings of the American Conference on Applied Mathematics*, Harvard University, MA, USA, pp. 209-213, 2008.

[2] J. Annette Von, B. Basudeb, "Assessment of Voltage Unbalance," *IEEE Transactions on Power Delivery*, vol. 16, no. 4, October 2001.

[3] S. H. Reyes, R. V. Jesus, "Identification of Unbalanced Loads in Electric Power Systems," *International Transactions on Electric Power Systems*, Vol. 24, pp. 1232-1243, 2014.

[4] C. Tsai-Hsiang, C. Jeng-Tyan, "Optimal Phase Arrangement of Distribution Transformers Connected to a Primary Feeder for System Unbalance Improvement and Loss Reduction Using a Genetic Algorithm," *IEEE Press*, Santa Clara, CA, USA, USA, 1999.

[5] B. S. Muhammad, A.J. Syed, F.A. Muhammad, and Z. Sajjad, "74. LV Three Phase Automatic Load Balancing System," in *4th International Conference on Energy, Environment and Sustainable Development (EESD)*, 2016.

[6] M. El Hassan, M. B. El Najjar, R. Tohme, "A Practical Way to Balance Single Phase Loads in a Three Phase System at Distribution and Unit Level", *Renewable Energy and Power Quality Journal* (RE&PQJ), ISSN 2172-038 X, Vol. 20, pp.173-177, September 2022.

[7] M. Fahim, *Balancing of Single Phase Loads in a Low Voltage Power System at the Distribution and Unit Level*, Doctoral Dissertation, Faculty of Engineering, University of Balamand, Lebanon, 2007. DOI:10.1109/ICIT.2018.8352365.

[8] W. M. Siti, A. Jimoh, D. Nicolae, "Distribution Network Phase Load Balancing as a Combinatorial Optimization Problem Using Fuzzy Logic and Newton– Raphson," *Electric Power Systems Research*, Vol. 81, No. 5, pp. 1079-1087, 2011.

[9] W. S. Mukwanga, V. N. Dan, A.J. Adisa, U. Abhisek, "Reconfiguration and Load Balancing in the LV and MV Distribution Networks for Optimal Performance," *IEEE Transactions on Power Delivery*, Vol. 22, No. 4, 2007.

[10] A. Ganga and K. Shilpa, "Loss Minimization Techniques Used in Distribution Network Bibliographical Survey," *Renewable and Sustainable Energy Reviews*, No. 29, pp. 184-200, 2014.

[11] W. T. Huang, K. C. Yao, Y. H. Huang, C. C. Wu, and C. H. Lo, "Load Balancing of Modern Distribution Networks by Genetic Algorithm," *Information Technology in Industry*, Vol. 5, pp. 1-6, 2016.

[12] A. Saffar, R. Hooshmand, and A. Khodabakhshian, "A New Fuzzy Optimal Configuration of Distribution Systems for Loss Reduction and Load Balancing Using Ant Colon Search-Based Algorithm," *Applied Soft Computing*, Vol. 11, pp. 4021-4028, 2011.