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# A RELAY-BASED AUTOMATIC BALANCING SYSTEM FOR THREE-PHASE LOADS IN INDUSTRY 4.0

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## ABSTRACT

The challenges of the existing industry to remain competitive have prompted the exploration of novel techniques that increase production, lessen waste, and enhance efficiency. The term "Industry 4.0" describes a new way of thinking about how technology might be used in manufacturing, mainly related to the Internet of Things (IoT), Big Data, and Cyber-Physical Systems (CPS). One of the main objectives of this fourth industrial revolution is the complete digitalization of the manufacturing chain in order to realize the interconnection of people, machines and devices. In light of this revolution, the investigation of an automatic balancing system (ABS) is something that interests us. In fact, an ABS is utilized to monitor and control three-phase loads in real time. The objective of this paper is to propose and implement a relay-based automatic balancing system using single-board computers (SBCs) as the main element to control the system operations, where sensors measure parameters like current, voltage, power, etc., in a three-phase load. The proposed system is capable of balancing the three-phase load by automatically switching the load phases between them, thus avoiding unbalanced load operation and the resulting problems.

**Keywords:** *Automatic Balancing System (ABS), Three-Phase Loads, Three-Phase Balancing, Industry 4.0, Industrial Internet Of Things (IIOT).*

## 1. INTRODUCTION

The current trend in manufacturing technologies is known as "Industry 4.0," which emphasizes data interchange and automation. Different techniques, such as cyber-physical systems are included, the Internet of Things, cloud computing, and cognitive computing [1]. One of the key enabling technologies of Industry 4.0 is the industrial internet of things (IIoT) [2]. IIoT is a term used to describe the integration of physical and cyber systems in manufacturing and other industrial sectors. The IIoT enables machines to communicate with each other and exchange data in real-time, allowing for a higher level of automation and flexibility [3].

A smart factory is a consequence of Industry 4.0 in which all of the machinery in the factory is connected to each other and is capable of speaking with one another and sharing data in order to achieve a desired outcome. This is made possible through the use of sensors, big data, and artificial intelligence (IA). Within the Industry 4.0 framework, manufacturing is seen as a system where physical, digital, and human components interact and cooperate flexibly to achieve high levels of performance and productivity [4].

Industry 4.0 has the ability to bring about a wide range of positive benefits. The potential for cost savings and productivity gains are just two examples. It could also lead to better goods and fresh commercial strategies[5].

A relay-based automatic balancing system for three-phase uses three relays, each of which is connected to one of the three phases of the load. They are connected in series so that they can be operated in parallel. When the system is turned on, the relays are activated and the current in the load is balanced. The balancing is achieved by the relay's opening and closing in a specific order, which is determined by the values of the currents in the three phases. The relays are controlled by a microcontroller, which receives the phase currents from sensors and determines the order in which the relays should be operated. The system is designed so that it can be used with any type of three-phase load [6].

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Manufacturing facilities that require a lot of electricity will be serviced by a three-phase grid from the utility company [7]. With this three-phase network, consumers must manage the installed electrical loads independently so that all three network sources are used equally [8]. This will cause a problem of complexity in the installation of the loads. Indeed, it is necessary to have clear data on the consumption of each phase in order to avoid having the loads gather on one of the phase wires and create an unbalanced system[9]. Furthermore, changing the installation of the loads for various reasons necessitates reconfiguring the previously installed loads [10].

Low-voltage residential power supplies are typically three-phase, four-wire systems in many parts of the world, fed by three-phase transformers. Although larger homes may have three-phase connections, the majority of homes only have a single-phase supply (i.e., one of the three phases and neutral). One of the most serious issues with these supplies' power quality is voltage unbalance[11].

Unbalanced three-phase loads in the industry can reduce efficiency, dependability, and safety. Unbalanced loads increase equipment wear, power quality, and safety risks. As sophisticated technologies like IoT, AI, and ML depend on a reliable power supply, unbalanced loads can significantly impact their performance and productivity. An intelligent balancing system could solve this problem. These system use AI, machine learning, and the Internet of Things to monitor and control three-phase power flow. This strategy can increase corporate productivity, dependability, and security. Industry 4.0 balancing systems increase real-time monitoring, predictive maintenance, power quality, safety, and cost. This improves coordination and performance under varied settings, making cutting-edge technologies more robust and adaptable. These industrial technologies may help companies reach Industry 4.0 ambitions.

We propose a relay-based automatic balancing system for three-phase loads, which has the added benefit of being suitable for any form of AC load (three-phase or single-phase). Here is how the rest of the paper is structured. The history of unbalanced systems is presented in the second part. The third part examines the relevant literature. In the fourth part, we focus on the most important aspects of our proposed approach. The findings and last thoughts are presented in the last part.

## 2. BACKGROUND

### 2.1 Industry 4.0 and the Industrial Internet of Things (IIoT)

The term Industry 4.0 was first coined in 2011 by a group of German economic experts to describe the fourth industrial revolution. This new industrial revolution is being driven by the Internet of Things (IoT) [12], Artificial Intelligence (AI) [13], big data and analytics, and additive manufacturing (3D printing). Together, these technologies are transforming normal factories into smart factories where machines are connected and can communicate with each other and with humans to make decisions independently [5].

The industrial internet of things (IIoT) is at the heart of Industry 4.0. It refers to the application of the IoT in manufacturing and other industrial sectors. The IIoT refers to the connection of machines, people, data, and processes to enable real-time communication and decision-making [14]. This is made possible by the use of sensors and actuators that are connected to the internet and can communicate with each other [15].

The IIoT is already having a transformative effect on manufacturing. For example, it is being used to monitor and optimize production processes in real-time. In the future, the IIoT is expected to enable the mass customization of products and the development of new business models [2].

The adoption of Industry 4.0 technologies is expected to result in a more flexible, agile, and responsive manufacturing sector. It will also lead to increased efficiency and productivity, as well as reduced costs.

### 2.2 Three-Phase System

In a three-phase system the current flows over three wires, and one neutral wire is used to conduct fault currents to the ground. As a result, the three-phase system refers to a system that employs three wires for power production, transmission, and distribution. Single-phase operation may be done by extracting one of the three-phase and the neutral wire. Adding the currents from the three phases equals zero, and their phases are separated by a 120° angle (Fig 1) [16].

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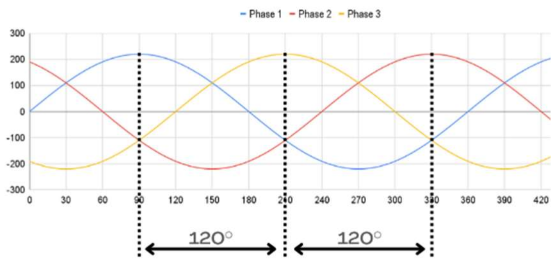


*Figure 1: Waveform Of A Three-Phase System*

### 2.3 Three-Phase Balanced and Unbalanced System/Load

A system with a balanced three-phase voltage or current has the same magnitude in each phase and phase angles that vary by 120 degrees from each other [17][18]. And, depending on the load, the resulting system will be either balanced or unbalanced [19]. Therefore, a three-phase system is considered balanced when each of its three phases has the same impedance as the others (Fig. 2, 3) and can be presented with the following equation:

$$I_1 = I_{1\,peak} * sin\ (\theta)\ (1)$$

$$I_2 = I_{2\,peak} * sin\ (\theta + \frac{2\pi}{3})\ (2)$$

$$I_3 = I_{3\,peak} * sin\ (\theta - \frac{2\pi}{3})\ (3)$$

$$I_{1\,peak} = I_{2\,peak} = I_{3\,peak}\ (4)$$

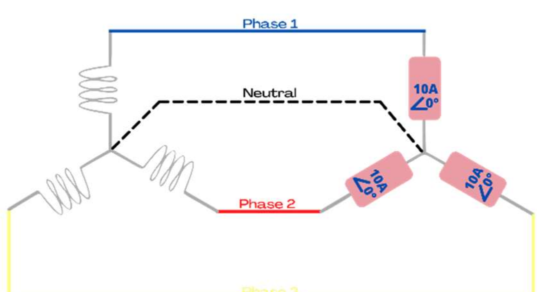


*Figure 2: Balanced System*

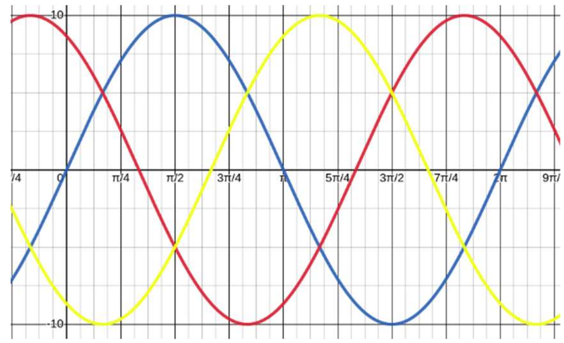


*Figure 3: Waveform Of A Balanced System*

Therefore, if the system is unbalanced, it is either due to a difference in magnitude (Figs. 4,5), which can be represented by the equation:

$$I_1 = I_{1\,peak} * sin\ (\theta)\ (5)$$

$$I_2 = I_{2\,peak} * sin\ (\theta + \frac{2\pi}{3})\ (6)$$

$$I_3 = I_{3\,peak} * sin\ (\theta - \frac{2\pi}{3})\ (7)$$

$$I_{1\,peak} \neq I_{2\,peak} \neq I_{3\,peak}\ (8)$$

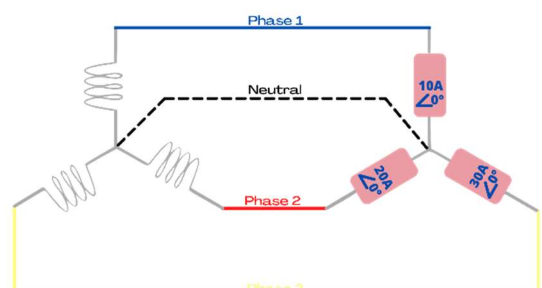


*Figure 4: Unbalanced System, The Difference In Magnitude*

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ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

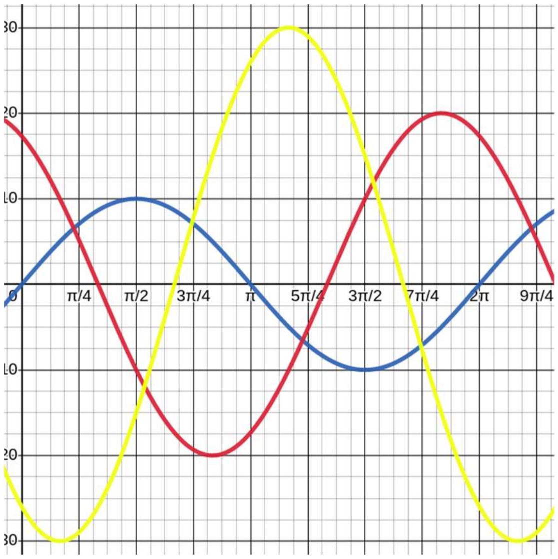


*Figure 5: Waveform Of An Unbalanced System, The Difference In Magnitude*

Or it is due to a phase difference (Figs. 6,7), which can be represented by the equation:

$$I_1 = I_{1\,peak} * sin\,(\theta + \alpha_1)\ (9)$$

$$I_2 = I_{2\,peak} * sin\,(\theta + \alpha_2)\ (10)$$

$$I_3 = I_{3\,peak} * sin\,(\theta + \alpha_3)\ (11)$$

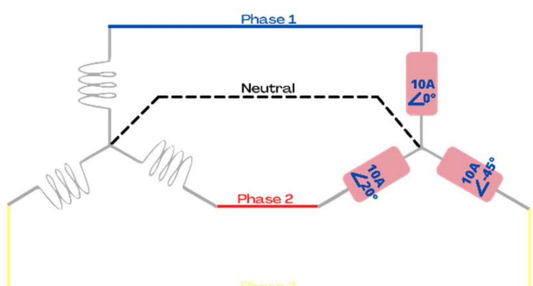


*Figure 6: Unbalanced system the difference in phase angle*

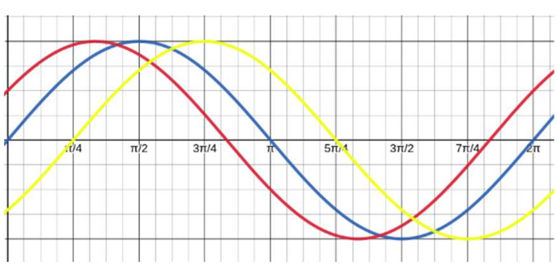


*Figure 7: Waveform Of An Unbalanced System, The Difference In Phase Angle*

## 3. RELATED WORKS

Aaron St. Leger et al. [20] proposed a methodology and architecture for a load management system for use in tactical microgrids. Load shedding and load balancing may be accomplished by rerouting loads to other phases. The 208/120 V 14.4 kVA prototype system's laboratory findings indicate the capacity to quickly transition loads between phases during an electrical cycle, allowing the system to continue operating with typical equipment (e.g., computers, lighting, air conditioning, etc.). according to other findings, a situation with an initial load disparity may be automatically brought back into equilibrium. The prototype can operate independently or as part of a larger hierarchical microgrid control system. The preliminary results of their research are promising in terms of enhancing the microgrid's performance by providing tactical microgrids with greater control and capabilities.

Sajid Ul Haq et al. [21] have presented an automated balancing system for household loads which is achievable owing to the proposed hardware, which is a microcontroller and relay-based hardware. It is mounted at the input of the three-phase lines and shifts the home load to the least loaded phase by utilizing quick-switching relays. Concerning lowering the three-phase line unbalance, it seems that the microcontroller and switching relays work well. In addition, it ensures voltage control and stability in all three phases.

I W Sutaya et al. [22] performed studies on single-phase load balancing systems in three-phase sources. According to the modeling studies, this system is capable of balancing single-phase loads on three-phase sources installed in consumers' power installations. In comparison to the first simulation experiment, the second simulation experiment generates better load balancing. This is due to the use of a varied number of load groups, with the second experiment utilizing six load groups whereas the first trial utilized five load groups.

Whereas all prior research on electrical load balancing has focused on single-phase loads, our method centers on three-phase loads. Balancing the load on a single-phase system is referred to as single-phase load balancing. The current across each phase must be equalized by connecting loads in a specific way. Simple to balance, single-phase systems are widely used in homes and small businesses. The number of phases to balance

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distinguishes single-phase and three-phase load balancing. Three-phase systems have three phases; single-phase systems have one. Three-phase systems require more complicated equipment and approaches to balance than single-phase systems.

## 4. PROPOSED METHODOLOGY

Our methodology is to add a PMCU (Power Monitoring and Control Unit) before each load, and they are all connected to the MCU (Main Control Unit) and an MPMU (Main Power Monitoring Unit) (Fig 8). The objective of this architecture is to allow the system to dynamically change the wiring of the loads in order to obtain an optimal balancing configuration. This architecture is based on Industry 4.0 technologies to achieve cost and time efficiency, and a core aspect is a continuous communication between devices for fast decision-making. To achieve such a feat, we needed IIOT-based devices.

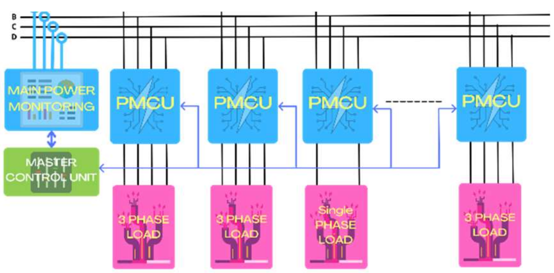


*Figure 8: The Schematic Diagram Of The Automatic Three-Phase Load Balancing That Is Proposed In This Research.*

Each PMCU is an IIoT device that consists of a power monitoring unit that can measure voltage, current, power factor, active power, reactive power, and apparent power, a switching system that can switch the wiring; and a control unit that can acquire data from the monitoring unit and control the switching system, and also communicate with the main control unit (Fig 9). First, we used an all-in-one power monitoring system (pm5100 from Schneider), but since the device can only give one packet every 100 milliseconds and we know that the frequency of the AC power supply is between 50 and 60 Hz and that the signal is sinusoidal, this means that we will have a period of 15 to 20 milliseconds, so one sample every six periods. Next, we created our own power monitoring board based on the ADE7785 (from Analog Devices), but since the device can only give one packet every 10 milliseconds, that is one sample per period. The final device is based on an 8-channel analog-to-digital converter with a sampling rate of 500kps (500,000 samples per second), which gives one packet every 0.85 milliseconds, or 1150 samples per period. For the switching system, we first used a normal relay with an operating time of 200 milliseconds, which means we can control the relays once every twelve periods, so we changed them to high-frequency relays with an operating time of 5 milliseconds which gives us the most control, to be exact, about four times for each period.

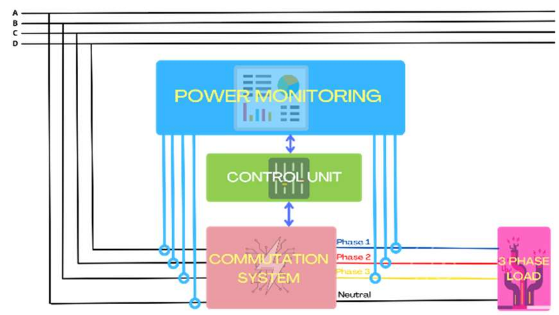


*Figure 9: The Schematic Diagram Of The Power Monitoring And Control Unit.*

The way that the system is designed to function is for each PMCU acquires data from its PMU (power monitoring unit) which is sent periodically to the main control unit or whenever the PMCU is started. Since each load has its own PMCU, this means that it is independent of the others. When an MPCU wants to connect a load to the power grid, it sends a request to the MCU. If the MCU has the history of that MPCU and the current data from the MPMU and other MPCUs, it sends the appropriate configuration. If it has no history, until it has enough information to deliver the proper configuration, it sends out a random one. In order to find the best possible setting, the MCU will occasionally broadcast updated configurations to other MPCUs. The commutation system is used by the MPCU control unit to switch the phases when it receives a configuration from the MCU, it may take a while for the switching to take place if the load is still consuming energy, but if the load can withstand the interruption to its normal operation, the switching will take place immediately.

We have four inputs (A, B, C, D) that we need to switch, so the switching system can be defined as a 4-by-4 relay matrix (Fig 10). But since the inputs are a three-phase system, the neutral must be fixed only when starting the MPCU, and only the three phases that must be switched when connecting a load to the electrical grid, so the switching system can be divided into two blocks (Fig 11). The first is a neutral detection and routing system (Fig 12), and the other is a 3-by-3 relay matrix for phase switching (Fig 13).

Journal of Theoretical and Applied Information Technology
15th March 2023. Vol.101. No 5


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Since the MPCU already has a PMU, we only need a routing system.

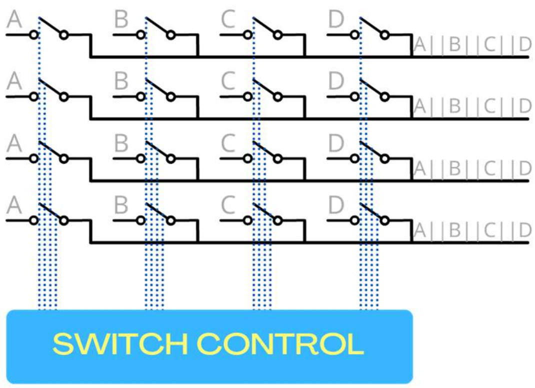


*Figure 10: The Schematic Diagram Of The 4-By-4 Relay Matrix.*

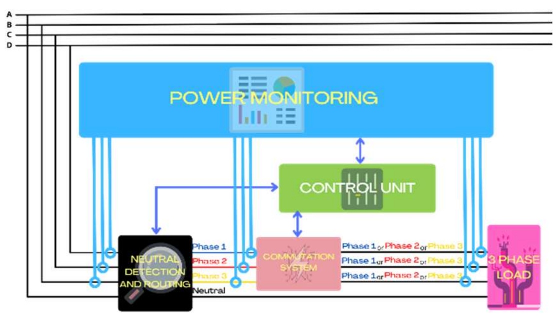


*Figure 11: The Schematic Diagram Of The Optimized Power Monitoring And Control Unit.*

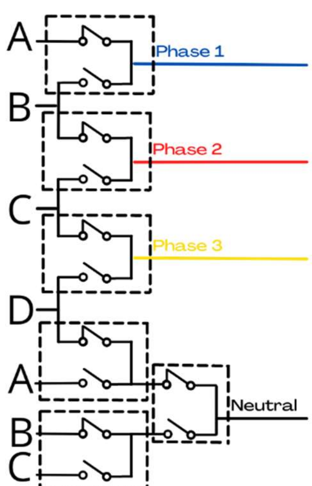


*Figure 12 The Schematic Diagram Of The Neutral Detection And Routing System.*

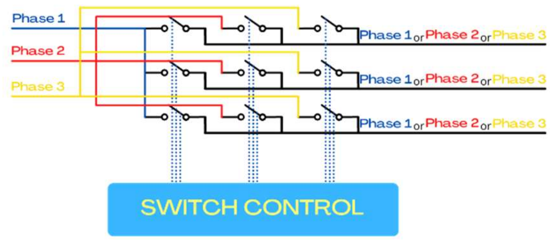


*Figure 13: The Schematic Diagram Of The Optimized 3-By-3 Relay Matrix.*

To find the optimal configuration, we must first find a way to compare two loads with a metric. As we know, the three-phase load has three current components $(I_1, I_2, I_3)$, so we can see it as a vector of three, and if we need to compare them, we just have to compare their magnitude (equation 12). The second thing is to convert a configuration into a single load, and for this, we need to add the current of all the loads for each phase (equations 13,14, and 15). The optimal configuration is the one with the minimum magnitude (equations 16 and 17). This needs to be repeated for each possible case. As shown in Table 1, the possible configuration for one load is six, so the possible configuration is $6^n$ (with n is the number of loads).

$$I_{m,x} = \sqrt{I_{1,x}^2 + I_{2,x}^2 + I_{3,x}^2} \quad (12)$$

$$I_{1,x} = \sum_0^n I_{1,i} \quad (13)$$

$$I_{2,x} = \sum_0^n I_{2,i} \quad (14)$$

$$I_{3,x} = \sum_0^n I_{3,i} \quad (15)$$

$$OC = min(I_{m,x}, I_{m,y}) \quad (16)$$

$$OC = \min(\sqrt{\sum_0^n I_{1,x,i}{}^2 + \sum_0^n I_{2,x,i}{}^2 + \sum_0^n I_{3,x,i}{}^2}, \sqrt{\sum_0^n I_{1,y,i}{}^2 + \sum_0^n I_{2,y,i}{}^2 + \sum_0^n I_{3,y,i}{}^2}) \quad (17)$$

*Table 1: Possible Configuration.*

| | | | |
|---|---|---|---|
| 0 | I1 | I2 | I3 |
| 1 | I1 | I3 | I2 |
| 2 | I2 | I1 | I3 |
| 3 | I2 | I3 | I1 |
| 4 | I3 | I1 | I2 |
| 5 | I3 | I2 | I1 |

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## 5. RESULTS AND DISCUSSION

The evaluation was conducted in five different plants, and in each of them, we randomly took ten unbalanced loads (Tab 2). For each plant, there will be an original table, a worst-configuration table, and an optimal configuration table. For the worst configuration, we need to change the min in equation (17) to the max (equation 18). We will also find the sum (equations 13,14, and 15), the magnitude (equation 12), and the unbalance percentage (equation 19).

$$WC = \max\left(\sqrt{\sum_0^n I_{1,x,i}^{\ 2} + \sum_0^n I_{2,x,i}^{\ 2} + \sum_0^n I_{3,x,i}^{\ 2}}, \sqrt{\sum_0^n I_{1,y,i}^{\ 2} + \sum_0^n I_{2,y,i}^{\ 2} + \sum_0^n I_{3,y,i}^{\ 2}}\right) \quad (18)$$

$$Unbalance(\%) = 100 * \frac{max(I_1,I_2,I_3) - min(I_1,I_2,I_3)}{min(I_1,I_2,I_3)} \quad (19)$$

As we can see, after each optimal configuration, the unbalance is less than 0.01% (equation 19), and in some cases, the worst configuration can be more than 200%. The approach was effective, and we even saw a reduction in power loss as a side effect. The tables below represent the power loss for each plant (Tab 8). For each plant, we took the value of the cable's resistance. The power loss can be calculated with equation (20) and, in our case, equation (21).

$$P = R * I^2 \quad (20)$$

$$P_{loss} = \sum_1^3 R * I_i^2 \quad (21)$$

*Table 2: The five plants and their appropriate unbalanced loads and currents.*

| Devices | Plant 1 | | | Plant 2 | | | Plant 3 | | | Plant 4 | | | Plant 5 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | I1 | I2 | I3 | I1 | I2 | I3 | I1 | I2 | I3 | I1 | I2 | I3 | I1 | I2 | I3 |
| **Dev 1** | 30.19 | 16.147 | 28.306 | 23.439 | 16.594 | 20.497 | 23.269 | 9.041 | 10.392 | 10.302 | 6.109 | 15.302 | 24.491 | 1.093 | 5.366 |
| **Dev 2** | 15.553 | 19.77 | 38.348 | 23.831 | 14.67 | 10.385 | 7.135 | 21.313 | 9.981 | 13.558 | 5.654 | 9.599 | 23.937 | 15.118 | 2.966 |
| **Dev 3** | 18.619 | 14.163 | 29.515 | 13.456 | 6.223 | 12.971 | 18.015 | 21.542 | 6.675 | 24.658 | 24.858 | 20.89 | 0.843 | 24.285 | 12.654 |
| **Dev 4** | 34.93 | 33.229 | 12.98 | 8.308 | 20.204 | 18.177 | 12.84 | 11.85 | 17.853 | 8.56 | 10.653 | 14.079 | 37.461 | 21.569 | 5.844 |
| **Dev 5** | 10.812 | 25.165 | 17.555 | 12.929 | 22.561 | 8.34 | 7.434 | 17.967 | 11.982 | 14.13 | 10.133 | 21.674 | 10.713 | 28.484 | 38.67 |
| **Dev 6** | 38.886 | 36.052 | 31.725 | 20.217 | 11.878 | 10.239 | 16.281 | 21.522 | 15.643 | 16.067 | 9.042 | 12.839 | 16.344 | 36.922 | 26.337 |
| **Dev 7** | 17.792 | 26.15 | 39.561 | 12.361 | 22.602 | 14.147 | 18.426 | 22.682 | 24.158 | 21.867 | 23.193 | 10.401 | 38.216 | 8.848 | 2.917 |
| **Dev 8** | 10.357 | 24.733 | 37.584 | 20.58 | 10.445 | 18.125 | 11.918 | 12.535 | 15.114 | 17.346 | 19.856 | 24.941 | 25.868 | 5.658 | 12.569 |
| **Dev 9** | 8.564 | 35.6 | 38.297 | 22.248 | 22.301 | 18.998 | 8.397 | 13.981 | 7.189 | 6.783 | 19.848 | 10.66 | 24.433 | 23.047 | 22.778 |
| **Dev 10** | 34.399 | 25.934 | 22.298 | 22.472 | 22.122 | 11.852 | 16.018 | 8.488 | 14.639 | 20.721 | 8.025 | 21.168 | 27.92 | 26.565 | 33.058 |

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*Table 3: The original, worst, and optimal configurations of the first plant.*

| Plant 1 | Original configuration | | | The worst configuration | | | | The optimal configuration | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | I1 | I2 | I3 | I1 | I2 | I3 | Cfg | I1 | I2 | I3 | Cfg |
| **Dev 1** | 30.19 | 16.147 | 28.306 | 30.19 | 28.306 | 16.147 | 1 | 28.306 | 30.19 | 16.147 | 4 |
| **Dev 2** | 15.553 | 19.77 | 38.348 | 38.348 | 19.77 | 15.553 | 5 | 15.553 | 38.348 | 19.77 | 1 |
| **Dev 3** | 18.619 | 14.163 | 29.515 | 29.515 | 18.619 | 14.163 | 4 | 18.619 | 14.163 | 29.515 | 0 |
| **Dev 4** | 34.93 | 33.229 | 12.98 | 34.93 | 33.229 | 12.98 | 0 | 12.98 | 33.229 | 34.93 | 5 |
| **Dev 5** | 10.812 | 25.165 | 17.555 | 25.165 | 17.555 | 10.812 | 3 | 25.165 | 17.555 | 10.812 | 3 |
| **Dev 6** | 38.886 | 36.052 | 31.725 | 38.886 | 36.052 | 31.725 | 0 | 31.725 | 38.886 | 36.052 | 4 |
| **Dev 7** | 17.792 | 26.15 | 39.561 | 39.561 | 26.15 | 17.792 | 5 | 17.792 | 26.15 | 39.561 | 0 |
| **Dev 8** | 10.357 | 24.733 | 37.584 | 37.584 | 24.733 | 10.357 | 5 | 37.584 | 24.733 | 10.357 | 5 |
| **Dev 9** | 8.564 | 35.6 | 38.297 | 38.297 | 35.6 | 8.564 | 5 | 35.6 | 8.564 | 38.297 | 2 |
| **Dev 10** | 34.399 | 25.934 | 22.298 | 34.399 | 25.934 | 22.298 | 0 | 34.399 | 25.934 | 22.298 | 0 |
| **Sum** | 220.102 | 256.943 | 296.169 | 346.875 | 265.948 | 160.391 | | 257.723 | 257.752 | 257.739 | |
| **Magnitude** | 449.645 | | | 465.592 | | | | 446.415 | | | |
| **Unbalance** | 34.56% | | | 116.27% | | | | 0.01% | | | |

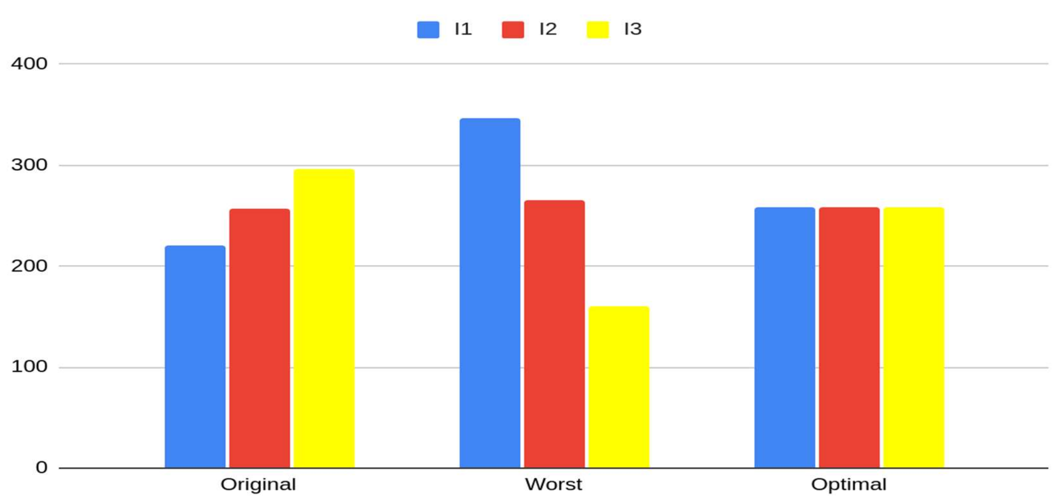


*Figure 14: The Original, Worst, And Optimal Unbalance Percentages Of The First Plant.*

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*Table 4: The original, worst, and optimal configurations of the second plant.*

| Plant 2 | Original configuration | | | The worst configuration | | | | The optimal configuration | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | I1 | I2 | I3 | I1 | I2 | I3 | Cfg | I1 | I2 | I3 | Cfg |
| Dev 1 | 23.439 | 16.594 | 20.497 | 23.439 | 20.497 | 16.594 | 1 | 16.594 | 20.497 | 23.439 | 3 |
| Dev 2 | 23.831 | 14.67 | 10.385 | 23.831 | 14.67 | 10.385 | 0 | 10.385 | 14.67 | 23.831 | 5 |
| Dev 3 | 13.456 | 6.223 | 12.971 | 13.456 | 12.971 | 6.223 | 1 | 13.456 | 12.971 | 6.223 | 1 |
| Dev 4 | 8.308 | 20.204 | 18.177 | 20.204 | 18.177 | 8.308 | 3 | 20.204 | 18.177 | 8.308 | 3 |
| Dev 5 | 12.929 | 22.561 | 8.34 | 22.561 | 12.929 | 8.34 | 2 | 22.561 | 12.929 | 8.34 | 2 |
| Dev 6 | 20.217 | 11.878 | 10.239 | 20.217 | 11.878 | 10.239 | 0 | 11.878 | 10.239 | 20.217 | 3 |
| Dev 7 | 12.361 | 22.602 | 14.147 | 22.602 | 14.147 | 12.361 | 3 | 14.147 | 12.361 | 22.602 | 4 |
| Dev 8 | 20.58 | 10.445 | 18.125 | 20.58 | 18.125 | 10.445 | 1 | 10.445 | 18.125 | 20.58 | 3 |
| Dev 9 | 22.248 | 22.301 | 18.998 | 22.301 | 22.248 | 18.998 | 2 | 22.248 | 22.301 | 18.998 | 0 |
| Dev 10 | 22.472 | 22.122 | 11.852 | 22.472 | 22.122 | 11.852 | 0 | 22.472 | 22.122 | 11.852 | 0 |
| Sum | 179.841 | 169.6 | 143.731 | 211.663 | 167.764 | 113.745 | | 164.39 | 164.392 | 164.39 | |
| Magnitude | 285.947 | | | 293.06 | | | | 284.733 | | | |
| Unbalance | 25.12% | | | 86.09% | | | | 0.00% | | | |

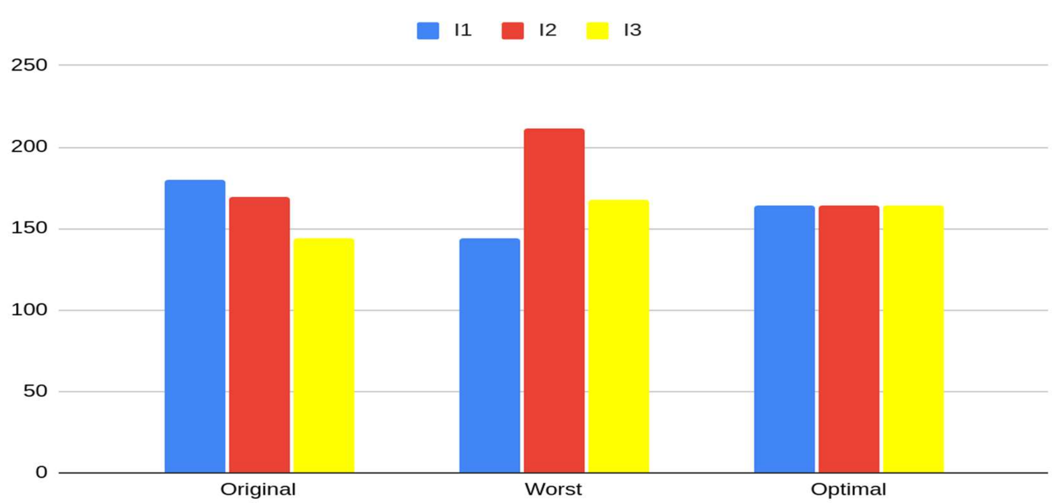

*Figure 15: The Original, Worst, And Optimal Unbalance Percentages Of The Second Plant.*

Journal of Theoretical and Applied Information Technology
15th March 2023. Vol.101. No 5

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*Table 5: The Original, Worst, And Optimal Configurations Of The Third Plant.*

| Plant 3 | Original configuration | | | The worst configuration | | | | The optimal configuration | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | I1 | I2 | I3 | I1 | I2 | I3 | Cfg | I1 | I2 | I3 | Cfg |
| Dev 1 | 23.269 | 9.041 | 10.392 | 23.269 | 9.041 | 10.392 | 0 | 9.041 | 10.392 | 23.269 | 3 |
| Dev 2 | 7.135 | 21.313 | 9.981 | 21.313 | 7.135 | 9.981 | 2 | 7.135 | 21.313 | 9.981 | 0 |
| Dev 3 | 18.015 | 21.542 | 6.675 | 21.542 | 6.675 | 18.015 | 3 | 18.015 | 21.542 | 6.675 | 0 |
| Dev 4 | 12.84 | 11.85 | 17.853 | 17.853 | 11.85 | 12.84 | 5 | 11.85 | 12.84 | 17.853 | 2 |
| Dev 5 | 7.434 | 17.967 | 11.982 | 17.967 | 7.434 | 11.982 | 2 | 11.982 | 7.434 | 17.967 | 4 |
| Dev 6 | 16.281 | 21.522 | 15.643 | 21.522 | 15.643 | 16.281 | 3 | 21.522 | 16.281 | 15.643 | 2 |
| Dev 7 | 18.426 | 22.682 | 24.158 | 24.158 | 18.426 | 22.682 | 4 | 22.682 | 24.158 | 18.426 | 3 |
| Dev 8 | 11.918 | 12.535 | 15.114 | 15.114 | 11.918 | 12.535 | 4 | 12.535 | 15.114 | 11.918 | 3 |
| Dev 9 | 8.397 | 13.981 | 7.189 | 13.981 | 7.189 | 8.397 | 3 | 13.981 | 7.189 | 8.397 | 3 |
| Dev 10 | 16.018 | 8.488 | 14.639 | 16.018 | 8.488 | 14.639 | 0 | 16.018 | 8.488 | 14.639 | 0 |
| Sum | 139.733 | 160.921 | 133.626 | 192.737 | 103.799 | 137.744 | | 144.761 | 144.751 | 144.768 | |
| Magnitude | 251.549 | | | 258.641 | | | | 250.732 | | | |
| Unbalance | 20.43% | | | 85.68% | | | | 0.01% | | | |

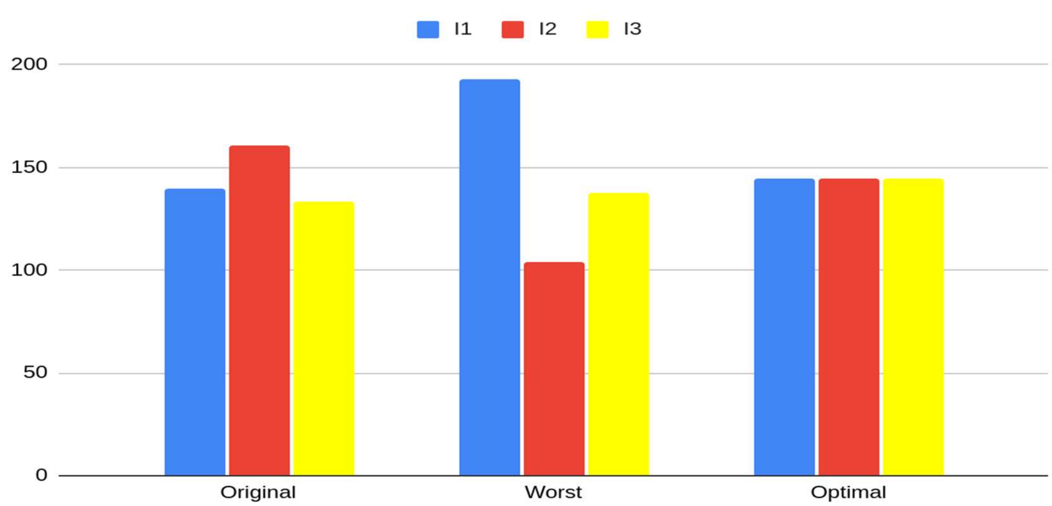

*Figure 16: The Original, Worst, And Optimal Unbalance Percentages Of The Third Plant.*

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*Table 6: The Original, Worst, And Optimal Configurations Of The Fourth Plant.*

| Plant 4 | Original configuration | | | The worst configuration | | | | The optimal configuration | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | I1 | I2 | I3 | I1 | I2 | I3 | Cfg | I1 | I2 | I3 | Cfg |
| Dev 1 | 10.302 | 6.109 | 15.302 | 10.302 | 6.109 | 15.302 | 0 | 15.302 | 6.109 | 10.302 | 5 |
| Dev 2 | 13.558 | 5.654 | 9.599 | 9.599 | 5.654 | 13.558 | 5 | 5.654 | 13.558 | 9.599 | 2 |
| Dev 3 | 24.658 | 24.858 | 20.89 | 24.658 | 20.89 | 24.858 | 1 | 24.658 | 24.858 | 20.89 | 0 |
| Dev 4 | 8.56 | 10.653 | 14.079 | 10.653 | 8.56 | 14.079 | 2 | 8.56 | 14.079 | 10.653 | 1 |
| Dev 5 | 14.13 | 10.133 | 21.674 | 14.13 | 10.133 | 21.674 | 0 | 10.133 | 21.674 | 14.13 | 3 |
| Dev 6 | 16.067 | 9.042 | 12.839 | 12.839 | 9.042 | 16.067 | 5 | 16.067 | 12.839 | 9.042 | 1 |
| Dev 7 | 21.867 | 23.193 | 10.401 | 21.867 | 10.401 | 23.193 | 1 | 21.867 | 23.193 | 10.401 | 0 |
| Dev 8 | 17.346 | 19.856 | 24.941 | 19.856 | 17.346 | 24.941 | 2 | 17.346 | 19.856 | 24.941 | 0 |
| Dev 9 | 6.783 | 19.848 | 10.66 | 10.66 | 6.783 | 19.848 | 4 | 10.66 | 6.783 | 19.848 | 4 |
| Dev 10 | 20.721 | 8.025 | 21.168 | 20.721 | 8.025 | 21.168 | 0 | 20.721 | 8.025 | 21.168 | 0 |
| Sum | 153.992 | 137.371 | 161.553 | 155.285 | 102.943 | 194.688 | | 150.968 | 150.974 | 150.974 | |
| Magnitude | 262.076 | | | 269.47 | | | | 261.491 | | | |
| Unbalance | 17.60% | | | 89.12% | | | | 0.00% | | | |

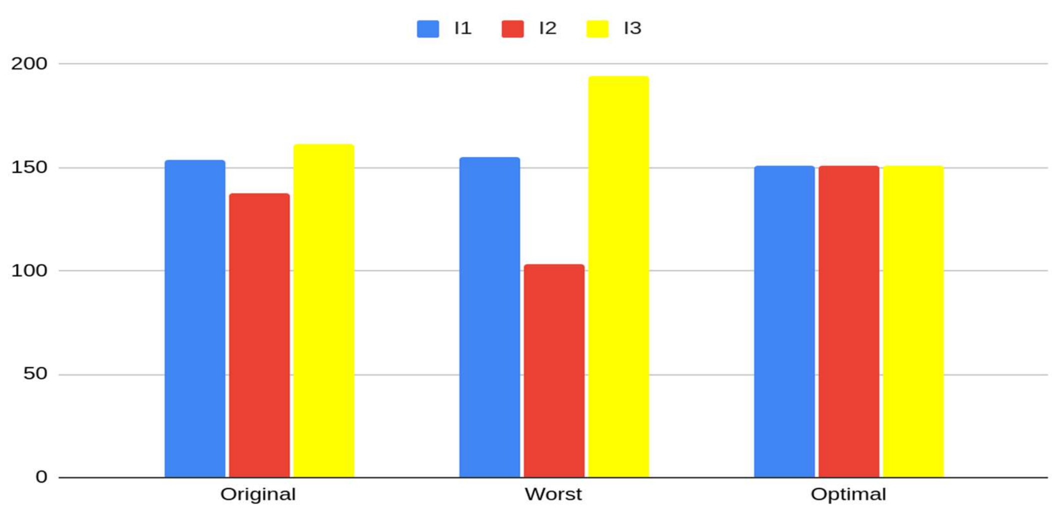


*Figure 17: The Original, Worst, And Optimal Unbalance Percentages Of The Fourth Plant.*

*Table 7: The Original, Worst, And Optimal Configurations Of The Fifth Plant.*

| Plant 5 | Original configuration | | | The worst configuration | | | | The optimal configuration | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | I1 | I2 | I3 | I1 | I2 | I3 | Cfg | I1 | I2 | I3 | Cfg |
| Dev 1 | 24.491 | 1.093 | 5.366 | 5.366 | 1.093 | 24.491 | 5 | 24.491 | 5.366 | 1.093 | 1 |
| Dev 2 | 23.937 | 15.118 | 2.966 | 15.118 | 2.966 | 23.937 | 3 | 2.966 | 15.118 | 23.937 | 5 |
| Dev 3 | 0.843 | 24.285 | 12.654 | 12.654 | 0.843 | 24.285 | 4 | 24.285 | 0.843 | 12.654 | 2 |
| Dev 4 | 37.461 | 21.569 | 5.844 | 21.569 | 5.844 | 37.461 | 3 | 21.569 | 5.844 | 37.461 | 3 |
| Dev 5 | 10.713 | 28.484 | 38.67 | 28.484 | 10.713 | 38.67 | 2 | 28.484 | 10.713 | 38.67 | 2 |
| Dev 6 | 16.344 | 36.922 | 26.337 | 26.337 | 16.344 | 36.922 | 4 | 26.337 | 36.922 | 16.344 | 5 |
| Dev 7 | 38.216 | 8.848 | 2.917 | 8.848 | 2.917 | 38.216 | 3 | 8.848 | 38.216 | 2.917 | 2 |
| Dev 8 | 25.868 | 5.658 | 12.569 | 12.569 | 5.658 | 25.868 | 5 | 5.658 | 25.868 | 12.569 | 2 |
| Dev 9 | 24.433 | 23.047 | 22.778 | 23.047 | 22.778 | 24.433 | 3 | 24.433 | 23.047 | 22.778 | 0 |
| Dev 10 | 27.92 | 26.565 | 33.058 | 27.92 | 26.565 | 33.058 | 0 | 27.92 | 33.058 | 26.565 | 1 |
| Sum | 230.226 | 191.589 | 163.159 | 181.912 | 95.721 | 307.341 | | 194.991 | 194.995 | 194.988 | |
| Magnitude | 341.074 | | | 369.747 | | | | 337.735 | | | |
| Unbalance | 41.11% | | | 221.08% | | | | 0.00% | | | |

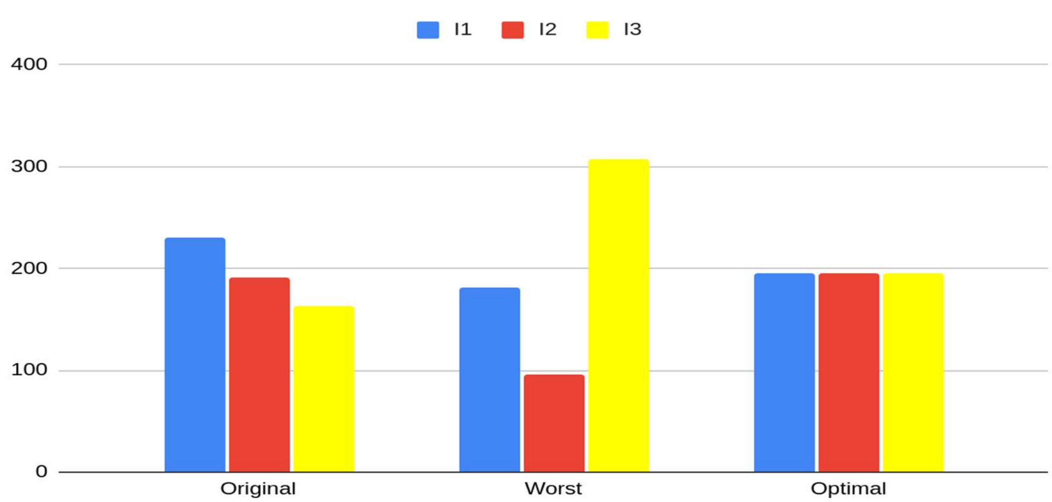


*Figure 18: The Original, Worst, And Optimal Unbalance Percentages Of The Fifth Plant.*

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## 6. CONCLUSION

In conclusion, the implementation of a balancing system that is based on Industry 4.0 can bring a wide variety of benefits for the industry as a whole. These systems monitor and control the distribution of electricity over all three phases of a three-phase system by integrating cutting-edge technology like the internet of things (IoT), artificial intelligence (AI), and machine learning (ML). This technology can boost efficiency, dependability, and safety in industries. Industry 4.0 balancing systems can improve power quality, safety, real-time monitoring and control, predictive maintenance, and cost. In the fourth industrial revolution, it can also improve the performance and coordination of modern technologies, making them more resilient and sensitive to changing situations (Industry 4.0).

Relay-based IIoT devices monitored parameters. The approach reduced three-phase load imbalance and power loss. It uses the configuration's minimum current vector magnitude. Since relays are slow, the method can only be implemented when a load is first activated or added to the power grid, even if the system functions in real time. Thus, TRIAC, SCR, etc. may improve the answer in future study. The algorithm needs 6^n potential scenarios, so the more loads we have, the longer it takes to find the ideal arrangement. Implementing AI and ML techniques to forecast the configuration and best rerouting of the three phases is another advancement.

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