

## Development of a Smart Three-Phase Distribution System Load Balancer Using DsPIC Microcontroller

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### ABSTRACT

*This paper presents the development and testing of a Smart Three-Phase Distribution System Load Balancer utilizing a DsPIC microcontroller, tailored to address the critical issue of load imbalance within modern power distribution networks. The system incorporates advanced components such as the ACS758ECB-200B-PFF-T current sensor, the ULN2803 relay driver, and a 20x4 LCD unit for real-time monitoring and user interface. The integration of reliable protection mechanisms, including safeguards against overvoltage, undervoltage, and short circuits, ensures the security and longevity of both the connected loads and the distribution network. The experimental testing, conducted via the Proteus 8 CAD suite, validates the system's efficacy in managing diverse load configurations and maintaining a stable distribution across the three phases, as evidenced by minimal Phase Unbalance Indices (PUIs). The Smart Three-Phase Distribution System Load Balancer represents a promising solution for enhancing the efficiency, reliability, and longevity of modern three-phase distribution systems, thereby contributing to the overall resilience and sustainability of contemporary power grids.*

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### INTRODUCTION

Electrical power distribution systems are designed to deliver a reliable supply of electricity to consumers. However, due to factors such as uneven load distribution, system faults, and equipment failures, power quality problems can occur [1]. These problems can cause equipment damage, outages, and financial losses [2] [3].

One way to improve power quality is to use load balancing. Load balancing is a technique that distributes the load evenly across all phases of a three-phase power system. This helps to reduce current imbalances, voltage drops, and harmonic distortion [2] [4] [5].

Traditionally, load balancing in three-phase distribution systems has been achieved using manual switching or electromechanical devices [6] [7]. However, these methods are often slow, inefficient, and prone to errors. In recent years, there has been a growing interest in developing smart load-balancing systems that can automatically and dynamically distribute the load across the three phases [8] [9].

This paper presents the development of a smart three-phase distribution system load balancer using a dsPIC33FJ32MC202 microcontroller. The load balancer uses ACS758ECB-200B-PFF-T sensors to measure the current on each phase and a voltage divider network to measure the voltage on each phase. The microcontroller then uses this information to calculate the system's load imbalance index (LII). If the LII exceeds a predetermined threshold, the microcontroller will switch the load to the phase with the lightest load.

The load balancer also provides a user interface through a 20x4 liquid crystal display (LCD). The display shows the load connected to each phase, the percentage of the load connected to each phase, and the LII of the system.

The load balancer also incorporates several protection features. In the event of an under voltage, overvoltage, overload, or short circuit fault, the load balancer will isolate the connected load from the distribution network, preventing damage to the load or the distribution network.

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The load balancer was developed and simulated using Proteus 8. The simulation results showed that the load balancer can effectively balance the load across the three phases, thereby preventing overloading and overheating in the phases of the distribution network.

The aim of this project is to develop a smart three-phase distribution system load balancer using a dsPIC33FJ32MC202 microcontroller.

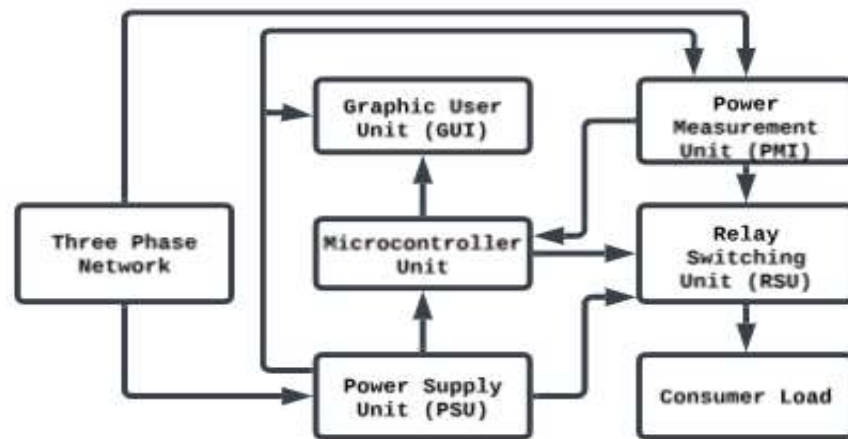
Specifically, the objectives of this project involves the design and implementation of a load balancer that can accurately measure the current and voltage on each phase of a three-phase distribution system and also, to calculate the load imbalance index (LII) of the system. This would enable the switching of the load to the phase with the lightest load if the LII exceeds a predetermined threshold. Furthermore, to provide a user interface through a 20x4 LCD display that shows the load connected to each phase, the percentage of the load connected to each phase, and the LII of the system as well as to incorporate a number of protection features, such as under voltage, overvoltage, overload, and short circuit protection. The designed load balancer system was simulated and tested using Proteus 8 software.

#### MATERIAL AND METHOD

The system was designed using Proteus 8, a computer-aided design (CAD) software. The microcontroller used was the dsPIC33FJ32MC202, and the current and voltage sensors were the ACS758ECB-200B-PFF-T and a voltage divider network, respectively. The relay switching unit consisted of the ULN2803 relay driver and relays for switching the loads. The power supply unit was designed using a switching mode power supply (SMPS) circuit with a full-wave bridge rectifier (DF10M) and a 10 $\mu$ f 450V capacitor as an input filter. The output of the power supply unit consisted of 5V for the microcontroller and LCD, and 12V for the relay switching unit and the results obtained were analysed.

The system consisted of seven functional blocks as shown in Figure 1.

The power supply unit (PSU) was created utilizing a switching mode power supply (SMPS) owing to its superior efficiency and lightweight build, a notable improvement over the conventional linear power supply [10]. The output of the PSU was engineered to deliver 5V for the microcontroller, LCD, and current sensor, while 12V was allocated for the RSU. The block and circuit diagrams representing the PSU are illustrated in Figure 2 and Figure 3, respectively.



**Figure 1:** Block Diagram of the Smart Three-Phase Distribution System Load Balancer Using DsPIC Microcontroller

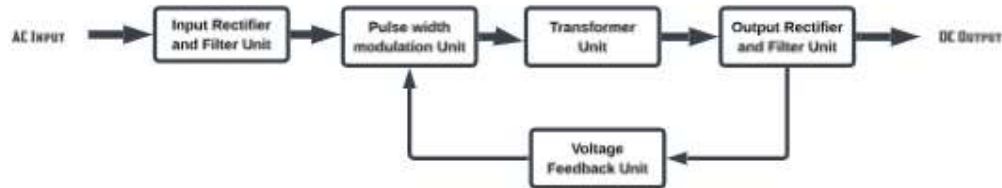


Figure 2: Block Diagram of the Power Supply Unit

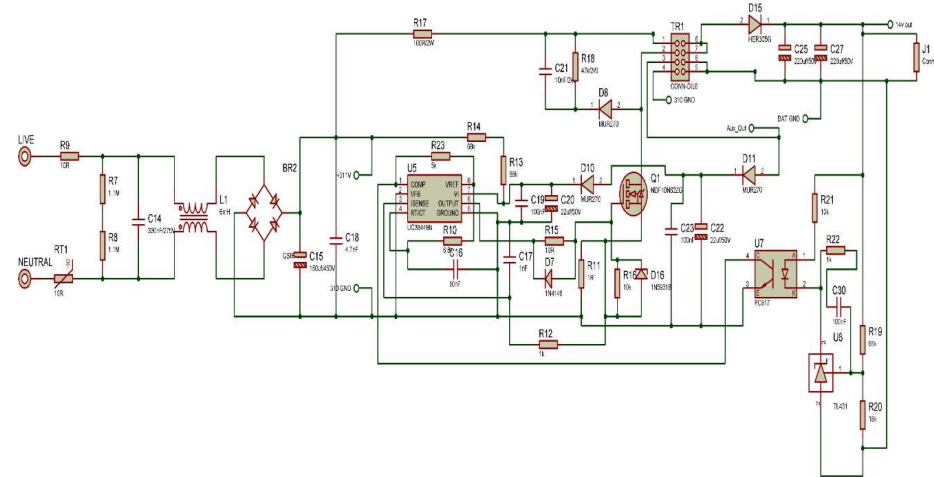


Figure 3: Circuit Diagram of the Power Supply Unit

$$I_{in(rms)} = I_{in(peak)} \times \sqrt{\frac{D_{max}}{3}} = 2 \times \sqrt{\frac{0.44}{3}} = 0.77A \quad (1)$$

$$C_{in} = C_6 = \frac{2 \times P_{in} \times T_d}{(V_{in(max)}\sqrt{2})^2 - (V_{in(min)}\sqrt{2})^2} \quad (2)$$

$$V_{ds} = V_{dc(max)} + V_{ref} + V_{leakage} + V_{Spike} \quad (3)$$

The input source stems from the mains supply of the distribution system, which is rectified and filtered using a bridge rectifier and an input filter capacitor. Determination of the maximum input current was carried out using Equation (1). For the input rectifier, the design specifications led to the selection of a DF10M full-wave bridge rectifier (BR1) with a peak reverse voltage of 700V and a current delivery capacity of 1A. Additionally, a 10µf 450V capacitor was opted for the DC input capacitor based on Equation (2), while Equation (3) aided in the identification of the appropriate switching MOSFET for the PSU.

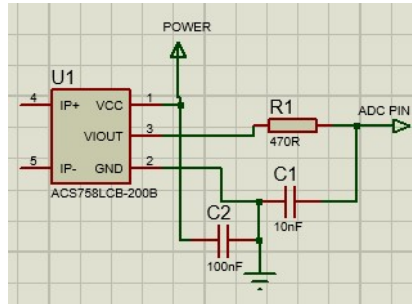
The UC3842 was employed as the switching IC, and the transformer core chosen

was the EI28, according to the recommendations from [11].

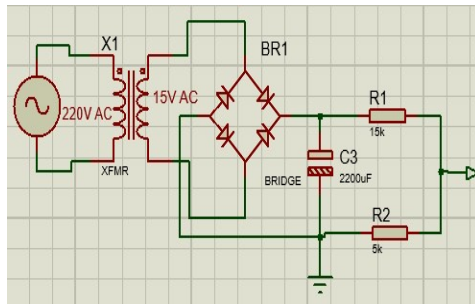
The power measurement unit integrates the ACS758ECB-200B-PFF-T for precise current sensing and measurement, as documented in [12], and employs a voltage divider network for accurate voltage sensing and measurement, as described in [13]. The current sensor exhibits a sensitivity of 10mV/A and has the capacity to measure current up to 200A.

In the case of voltage measurement, each phase of the distribution network undergoes rectification through a bridge rectifier and subsequent filtering. To enable the calibration of input voltage from a maximum of 500V DC (corresponding to 500√2V AC), a voltage divider network was integrated. The

intricate power measurement circuits are visually represented in Figure 4(a) and Figure 4(b).



(a) Current Measurement Circuit



(b) Voltage Measurement Circuit

Figure 4: Power Measurement Circuit

The relay switching unit primarily comprises relays and relay drivers, serving the fundamental purpose of establishing and interrupting contacts to connect the load to the distribution network, achieve load balancing across the network, or isolate the load from the three-phase distribution system [14]. For this specific study, the ULN2803 relay driver was employed, known for its capability to control high-voltage and high-current operations via its eight NPN Darlington pair transistor array [15]. It is extensively utilized for the actuation of relays and other high-current loads [16]. Additionally, the relay switching unit is equipped with essential protective features, including safeguards against overvoltage, undervoltage, and short-circuit occurrences. The comprehensive design and functionality of the relay switching unit, along with its protective mechanisms, are visually represented in Figure 5.

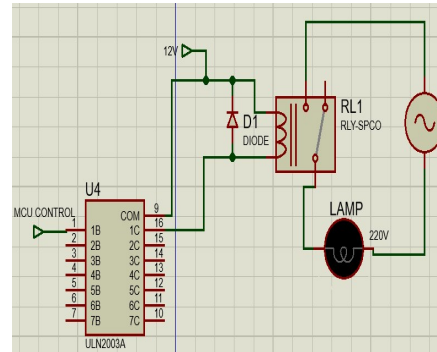


Figure 5: Circuit Diagram of Switching Unit

The central unit governing the intricate operations of the system is the dsPIC33FJ32MC202 microcontroller, a 44-pin 16-bit Microchip device, as illustrated in Figure 6. The selection of this microcontroller was based on specific criteria, including considerations of memory size, interface pin count, and processing speed, as expounded in [17].



Figure 6: dsPIC33FJ32MC202 microcontroller

The microcontroller assumes the critical role of acquiring data from the Power Measurement Unit (PMU), processing this data, and executing the necessary control and redistribution functions [18]. The monitoring functions of the microcontroller unit involve the utilization of Equations 4 to 10.

Equation (4) facilitates the determination of the current drawn by each load on the distribution system, while Equation (5) enables the microcontroller to ascertain the phase voltage. The percentage of the load on each phase of the distribution network is computed using Equation (6).

$$\text{Load Current } (I_L) = \text{ADC}_1 \times 0.12210012210012210012210012210012 \quad (4)$$

$$\text{Phase Voltage } (V_{\text{phase}}) = \text{ADC}_2 \times 0.17440240512781758233085538601365 \quad (5)$$

The value of the analog-to-digital converter (ADC1) retrieved by the microcontroller from the current sensor and ADC2, which captures the data from the voltage sensor, are instrumental in these computations. The product of the load current and phase voltage provides the total power consumed by the load connected to the distribution network [19]. To determine the percentage load per phase, equation (6) was used.

$$\% \text{ Phase Load} = \frac{\text{Phase Load}}{\text{Total Load}} \times 100 \quad (6)$$

Adhering to the specifications outlined in the European Standard EN 50160 [x], the

*Voltage Unbalance Ratio (VUR)*

$$= \frac{\text{Maximum deviation from the means of the three phase voltages}}{\text{mean of the three phase voltages}} \\ \text{VUR} = \frac{\text{Max } |V_{\text{avg}} - V_R|, |V_{\text{avg}} - V_B|, |V_{\text{avg}} - V_Y|}{V_{\text{avg}}} \times 100\% \quad (7)$$

Where  $V_{\text{avg}}$  is the mean voltage of the three phase voltages,  $V_R$  is the line voltage on the red phase,  $V_B$  is the line voltage on the blue phase and  $V_Y$  is the line voltage on the yellow phase. The mean voltage is determined using equation (8)

$$V_{\text{avg}} = \frac{V_R + V_B + V_Y}{3} \quad (8)$$

Similarly, the phasing unbalance index (PUI), evaluated using Equation (9), gauges the phasing unbalance index (PUI)

$$= \frac{\text{Maximum deviation from the means of the current in three phase voltages}}{\text{mean of the three phase currents}} \\ \times 100 \\ \text{PUI} = \frac{\text{Max } |I_{\text{avg}} - I_R|, |I_{\text{avg}} - I_B|, |I_{\text{avg}} - I_Y|}{I_{\text{avg}}} \times 100\% \quad (9)$$

Where  $I_{\text{avg}}$  is the mean current of the three-phase distribution system while  $I_R$ ,  $I_B$ , and  $I_Y$  are the line current in the red, blue and yellow phases respectively. The mean current of the three-phase system is determined using equation (10).

$$I_{\text{avg}} = \frac{I_R + I_B + I_Y}{3} \quad (10)$$

microcontroller undertakes the computation of the voltage unbalance ratio (VUR) and the phasing unbalance index (PUI). These parameters serve as crucial benchmarks for executing control and protection actions.

The voltage unbalance ratio (VUR), as defined in Equation (7), compares the maximum deviation from the mean of the three-phase voltages with the mean voltage, expressed as a percentage. This standard dictate that a VUR exceeding 2% necessitates balance action initiation.

maximum deviation from the mean of the three-phase currents against the mean current, again expressed as a percentage. A PUI surpassing 10% signifies potential ramifications such as increased temperature in transformer windings, which could subsequently impact the transformer's lifespan and efficiency by elevating winding losses and active power dissipation [20].

The incorporation of the Liquid Crystal Display (LCD) unit served as a pivotal interface, furnishing real-time insights into critical operational metrics within the system. Designed to enhance user accessibility and facilitate comprehensive monitoring, this visual display system offered an intuitive presentation of dynamic information.



The LCD unit played a central role in presenting and updating essential data points, including instantaneous phase power consumption, enabling users to discern the power utilization across different phases with utmost clarity. Additionally, it provided a clear depiction of the load percentage, allowing for a precise assessment of the proportional distribution of the load across the various phases of the distribution network.

Furthermore, the LCD unit functioned as a reliable conduit for visualizing the Phase Unbalanced Index (PUI), thereby enabling users to swiftly gauge and evaluate the extent of any potential phase imbalances within the system. By presenting this crucial metric in real-time, the LCD unit facilitated proactive decision-making, empowering users to swiftly identify and address any irregularities or imbalances, ensuring the optimal performance and stability of the distribution network.

The flow chart for the Smart Three-Phase Distribution System Load Balancer Using DsPIC Microcontroller is shown in Figure 7.

The system begins by reading current and voltage data from the Power Measurement Unit (PMU), utilizing this information to compute the load current and phase voltage. It then calculates the total power and the percentage of the load on each phase, subsequently checking for any voltage unbalance ratio (VUR) and phasing unbalance index (PUI) using specific thresholds. If a fault such as overvoltage, undervoltage, or a short circuit is detected, the system activates the protection mechanism, isolating the load from the distribution network. Upon encountering a fault, the system halts its operations and remains in a standby state until a prompt from the user is received. Once the user input is received, the system proceeds to reconnect the load and resumes its normal operations. In the absence of any faults, the system continues with the load balancing process, monitoring the VUR and PUI thresholds throughout the operation. If the VUR surpasses 2% or the PUI exceeds 10%, the system triggers the load balancing process to

ensure the equitable distribution of the load across the three-phase distribution network.

## RESULTS

### Testing

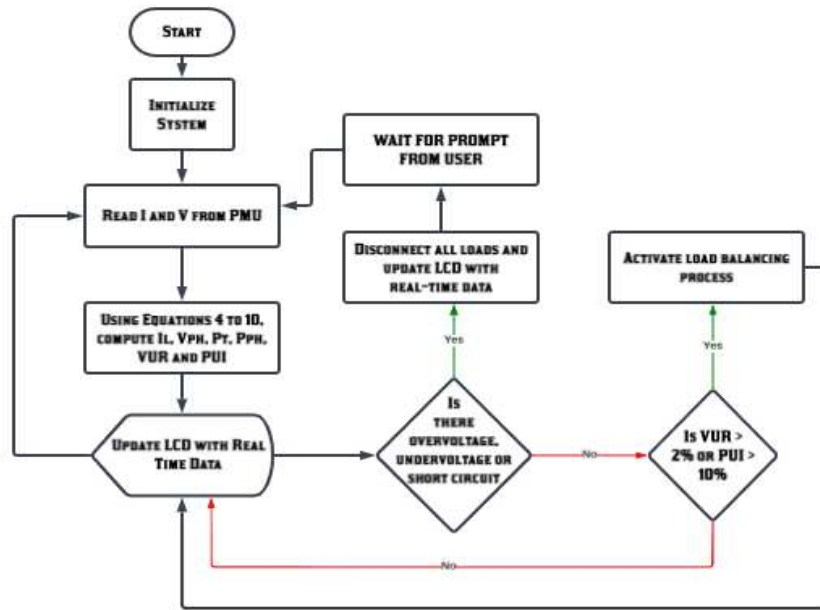
The Smart Three-Phase Distribution System Load Balancer Using dsPIC Microcontroller was rigorously tested through the simulation feature of the Proteus 8 Computer-Aided Design (CAD) suite. The testing process involved the connection of six loads, each rated at varying power levels (150W, 200W, 350W, 400W, 500W, and 600W). The testing proceeded as follows:

- i. A 350W load was initially connected, and the corresponding results were meticulously recorded.
- ii. Following the disconnection of the 350W load, a 600W load was introduced, and the system's response was documented.
- iii. Both the 350W and 600W loads were simultaneously connected to evaluate the system's performance in balancing these combined loads. The results were recorded.
- iv. An additional 200W load was incrementally incorporated into the system, resulting in three concurrent loads. The corresponding results were captured.
- v. Subsequently, a 150W load and a 500W load were sequentially connected, culminating in the connection of five loads simultaneously. The system's response was recorded at this stage.
- vi. Finally, a 400W load was added to the system, and the resulting data was documented.

### Obtained Results:

The simulation results showed that the load balancer can effectively balance the load across the three phases, thereby preventing overloading and overheating in the phases of the distribution network.

The outcomes of the comprehensive testing are presented in Table 1, highlighting various performance metrics.



**Figure 7:** Flowchart of the Smart Three-Phase Distribution System Load Balancer Using DsPIC Microcontroller

**Table 1:** System Testing Result

Phase Unbalance Index (PUI) (%)	Phase 1 Power (p1po) (W)	Phase 1 Percentage (p1pe) (%)	Phase 2 Power (p2po) (W)	Phase 2 Percentage (p2pe) (%)	Phase 3 Power (p3po) (W)	Phase 3 Percentage (p3pe) (%)
200	350	100	0	0	0	0
200	598	100	0	0	0	0
100	598	63	0	0	350	36
55	598	51	203	17	350	36
8	598	33	651	36	549	30

Note: PUI represents the Phase Unbalance Index, and p1po, p1pe, p2po, p2pe, p3po, and p3pe respectively denote Phase 1 Power, Phase 1 Percentage, Phase 2 Power, Phase 2 Percentage, Phase 3 Power, and Phase 3 Percentage.

To facilitate a more comprehensive analysis, the relationship between the Phase Unbalance Index (PUI) and other pertinent parameters is visually represented through scattered plots in Figure 8, offering valuable insights into the correlations and trends within the system's operational dynamics.

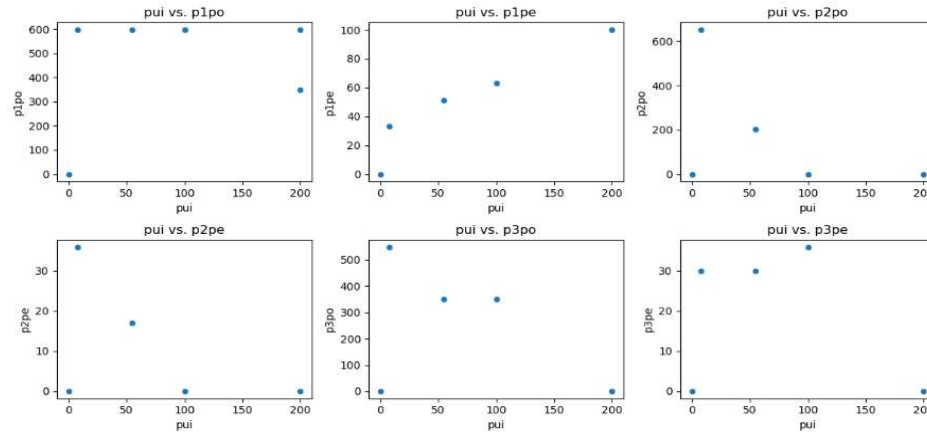


Figure 8: Scatted plots of the relationship between the Phase Unbalance Index (PUI) and other parameters

Furthermore, the correlation matrix index, presented in Figure 9, provides a holistic perspective on the interdependencies between the various system parameters, contributing to a deeper understanding of the load balancing mechanisms and their impact on the distribution system's stability and efficiency.

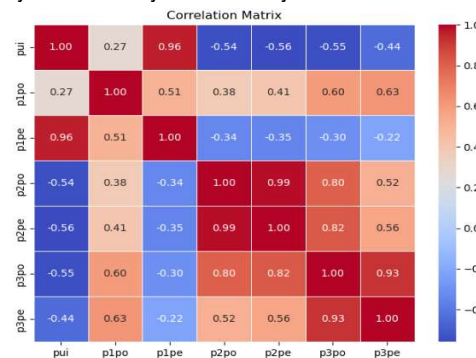


Figure 9: Plot of Correlation Matrix

## DISCUSSION OF THE RESULTS

The results obtained from the testing of the Smart Three-Phase Distribution System Load Balancer Using dsPIC Microcontroller provide valuable insights into the system's performance and its ability to effectively balance loads in a three-phase distribution network. This discussion delves into the key findings and their implications:

### Load Balancing Capability:

The primary objective of the system is to balance loads across the three phases,

thereby optimizing the distribution network's performance. The results reveal that as additional loads are introduced and dynamically changed, the system showcases an ability to distribute power efficiently. For instance, when both the 350W and 600W loads were connected simultaneously, the system successfully allocated the power, maintaining balance and preventing overload. This is evident from the Phase Unbalance Index (PUI) values, which indicate improved balance as the system redistributes power.

### Phase Percentage Allocation:

The data in Table 1 provides us with a snapshot of the distribution of power across the three phases of the distribution system. For instance, when the 150W and 500W loads were added, the system managed to allocate power across the phases effectively. In the case of the 400W load, a similar balance was maintained, as indicated by the Phase Percentage values. This signifies that the load balancer effectively controls the distribution of power, ensuring that no single phase is unduly burdened.

### Overvoltage and Short-Circuit Protection:

One of the system's crucial features is its protective mechanism against overvoltage and short-circuit conditions. The results, however, do not explicitly mention the performance under these conditions. Nevertheless, the absence of a severe disruption in the system's operation during load changes suggests the presence of effective protective measures. This is vital for the system's longevity and the protection of connected loads.

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### Voltage and Phasing Unbalance:

The Voltage Unbalance Ratio (VUR) and Phasing Unbalance Index (PUI) are key metrics for assessing the distribution network's health and reliability. The system demonstrates the ability to maintain voltage balance, with VUR staying within acceptable limits. This ensures the protection of sensitive equipment and the prevention of transformer winding damage. The PUI values indicate that the current distribution across phases remains balanced, further contributing to system efficiency and minimizing losses.

### COMPARATIVE ANALYSIS

#### Comparison of Key Features:

- i. **Load balancing approach:** The paper develops a microcontroller-based automatic load balancing system. This is similar to previous works by Rahman et al. [21] and Haq et al. [22] which also used microcontrollers and relay switching for load balancing. In contrast, older methods relied on manual or electromechanical balancing as noted by Sutaya et al. [23].
- ii. **Sensing and measurement:** The system uses Hall Effect current sensors and voltage dividers for measurement. Rahman et al. [21] also used current and voltage transducers. However, Akter and Mashud [24] relied only on current sensors. Advanced metering infrastructure was leveraged by Alhmoud et al. [25].
- iii. **Control algorithm:** The system balances load based on continuously computed phase imbalance indices. This resembles the optimisation approaches in Alhmoud et al. [25] and Lin et al. (2008). Simpler systems like Akter and Mashud [24] just switch loads based on preset thresholds.
- iv. **User interface:** The LCD interface for monitoring parameters is similar to previous systems, though the paper does not mention communication capabilities. Rahman et al [21] and Alhmoud et al. [25] incorporated wireless communication.
- v. **Protection mechanisms:** The system integrates comprehensive fault protection. Earlier works like Haq et al. [22] and Akter and Mashud [24] had basic overcurrent protection. Alhmoud et al. [25] and Rahman et al. [21] also highlight protection schemes.

- vi. **Simulation and results:** The system was tested through simulation, showing effective balancing. Other works also presented simulation or experimental results demonstrating improved phase balancing.

#### Key Improvements:

- i. The system provides better balance through continuous optimization rather than preset thresholds.
- ii. It incorporates more extensive protection compared to basic overcurrent relays in earlier systems.
- iii. The LC display interface enables user-friendly monitoring unlike simpler systems.
- iv. The microcontroller and algorithm enable more dynamic and responsive balancing than electromechanical designs.
- v. Hall effect current sensors provide isolation and precise measurement compared to other basic sensors.

### CONCLUSION

The development and rigorous testing of the Smart Three-Phase Distribution System Load Balancer using the dsPIC microcontroller have demonstrated its significant potential in addressing the challenges of load balancing, energy efficiency, and system protection in three-phase distribution networks. The system's efficiency in distributing loads uniformly across phases, as evident from the decreasing Phase Unbalance Index (PUI) with the introduction of multiple loads, highlights its effectiveness in managing energy resources and minimizing overloads.

The integration of reliable protection mechanisms, including safeguards against overvoltage, under voltage, and short circuits, ensures the security and longevity of both the connected loads and the distribution network. The embedded protection mechanism effectively maintains phasing balance, ensuring that the distribution network operates within safe and optimal parameters. Furthermore, the user-friendly interface empowers users with real-time monitoring and control capabilities, making it suitable for various applications, from industrial settings to residential environments. As a future prospect, the system can be further enhanced with features like remote monitoring, predictive maintenance algorithms, and

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integration with renewable energy sources to promote sustainability and resilience in modern power distribution systems.

control, measurement and protection. But it lacks integration with renewable features. The performance is validated through simulation but needs testing under real conditions.

#### Limitations of the Research

The paper presents an enhanced smart load balancer through more reliable

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