Solar Energy
And Sustainable Development
Refereed, biannual scientific journal issued by:
The Libyan Center for Solar Energy Research and Studies

Development of an Optimal Control Strategy of Three Phase Power Factor Correction System

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ARTICLE INFO.

Article history:
Received 7 Jul 2025
Received in revised form 21 Aug 2025
Accepted 25 Aug 2025
Available online 9 Sep 2025

KEYWORDS

Optimal control; three phases; power factor correction; energy losses; energy efficiency.

ABSTRACT

The efficient provision of electric power is regarded as a critical issue for both energy suppliers and customers. The power factor, as a measure of system efficiency, is essential for minimizing energy losses and ensuring reliable power output. An insufficient power factor, primarily caused by elevated inductive loads, results in increased line currents, heightened power losses, and significant voltage drops, hence reducing system reliability and inflating energy costs. To address this, power factor correction techniques are typically employed, mostly including the integration of capacitive loads to counteract inductive effects.

This study investigates the development of a three-phase power factor correction panel utilizing an ideal methodology to achieve designated power factor levels. The primary objective of this study is to develop a three-phase automatic power factor correction system that employs an optimization method to determine the optimal capacitor combination to improve the power factor to a reference-defined level. The general modified optimization method reduces the operation of switching contactors by a minimum of four times, up to the third dynamic power factor correction, compared to the staged approach (which entails checks and adjustments). Additionally, it reduces transients by the implementation of different operational strategies for the insertion or removal of capacitors, hence improving accuracy and stability while maintaining both within acceptable parameters.

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DOI: https://doi.org/10.51646/jsesd.v14i2.660

تطوير استراتيجية التحكم الأمثل لنظام تصحيح معامل القدرة ثلاثي الطور

محمد الدريدي، وائل عبد المهدي صلاح، محمد السفاريني.

ملخص: تُعدّ كفاءة إمدادات الطاقة مصدر قلق رئيسي لكل من مُزوّدي الطاقة والمستهلكين. يُعدّ معامل القدرة، كمؤشر على كفاءة النظام، بالغ الأهمية لتقليل خسائر الطاقة وضمان إنتاج طاقة موثوق. يؤدي معامل القدرة غير الكافي، والذي يُعزى غالبًا إلى ارتفاع الأحمال الحثية، إلى زيادة تيارات الخطوط، وزيادة خسائر الطاقة، وانخفاضات كبيرة في الجهد، مما يُقلل من موثوقية النظام ويرفع تكاليف الطاقة. وللتخفيف من ذلك، تُستخدم طرق تصحيح معامل القدرة بشكل شائع، والتي تشمل عادةً دمج الأحمال السعوية لتعويض التأثيرات الحثية. تبحث هذه الدراسة في إنشاء لوحة تصحيح معامل القدرة ثلاثية الأطوار باستخدام نهج أمثل للحصول على مستويات مُحددة لمعامل القدرة. الهدف الرئيسي من هذه الدراسة هو تطوير لوحة تصحيح معامل القدرة التلقائي ثلاثية الأطوار باستخدام طريقة تحسين تختار أفضل تركيبة من المكثفات لرفع معامل القدرة إلى مستوى مرجعي مُحدد. يُقلل نهج التحسين المُعدّل العام من تشغيل مُلامسات التبديل بأربع مرات على الأقل، حتى تصحيح معامل القدرة الديناميكي الثالث، مقارنةً بالطريقة المُتدرجة (التي تتضمن عمليات فحص وتعديل). علاوةً على ذلك، يُقلل من التذبذبات العابرة من خلال استخدام استراتيجيات تشغيل مُتنوعة لإدخال أو إزالة المُكثّفات، مما يُعزز الدقة والاستقرار مع الحفاظ على كليهما ضمن الحدود المقبولة.

الكلمات المفتاحية – التحكم الأمثل؛ ثلاث مراحل؛ تصحيح معامل القدرة؛ خسائر الطاقة؛ كفاءة الطاقة.

1. INTRODUCTION

Energy is the driving force behind various aspects of life today, with the demand for electrical power increasing day by day to meet the growing needs [1-3]. Therefore, there is a great effort been taken to have an alternative sustainable source [4-8]. Additionally, a lot of work has been done to increase the quality and optimize energy use. By measuring each appliance's energy use, consumers can optimize their energy use by taking the necessary actions [9-11].

Power quality issues have gained significant relevance, particularly with power factor, unbalanced current, voltage drop, and other factors that negatively influence the performance and efficiency of electrical systems [12, 13]. In both industry and domestic applications, the majority of loads are inductive loads in nature that are being used [14, 15]. As a result, the use of these inductive loads is main reason for low power factor in power system [16, 17]. Consequently, there emerged a necessity to devise a system for the automatic enhancement of power factor [18, 19]. A low power factor imposes an unneeded strain on the power system and transmission lines [20]. Enhancing the power factor of a power system automatically might increase its efficiency [21, 22].

The power factor is the ratio of kilowatts (KW) to kilovolt-amperes (KVA) consumed by an electrical load, where KW represents the actual load power and KVA denotes the perceived load power. This metric assesses the efficacy of current conversion into productive work output and serves as a reliable indicator of the impact of load current on the efficiency of the supply system. Power factor adjustment is accomplished by incorporating capacitors in parallel with the motor circuits, which can be implemented at the starting or at the switchboard or distribution panel. The resultant capacitive current is a leading current utilized to counteract the lagging inductive current emanating from the source [23-26].

The correction of the power factor will diminish power line losses, enhance system and device efficiency, decrease voltage drop, minimize conductor and cable dimensions, thereby reducing copper costs, facilitate the appropriate sizing of electrical machines such as transformers and generators, eliminate penalties for low power factor imposed by electric supply companies, yield savings on power bills, optimize the utilization of power systems, lines, and generators, and ultimately lower the ratings and costs of electrical devices and equipment [27-30].

The world is increasingly relying on renewable energy sources of varying types in response to climate change and the rise in carbon emissions that are a consequence of the use of traditional energy sources [31-37]. This transformation requires the existence of a network that is capable of assimilating the diverse and ever-changing quantity of energy sources [38, 39]. The power factor is a critical factor for electricity suppliers in the context of renewable energy, and it is receiving heightened attention, particularly when networks are connected to renewable energy sources [40, 41]. Power Factor Correction (PFC) techniques are essential in renewable energy applications to ensure that the generated power is delivered efficiently and with the fewest potential losses. PFC systems contribute to the stability of the grid, enhance the compatibility of renewable energy sources with the existing grid infrastructure, and decrease harmonic distortions and power factor [42]. These factors, in turn, result in more sustainable and stable energy delivery. Consequently, the integration of sophisticated PFC strategies is a critical factor in the widespread and efficient adoption of renewable energy technologies. The high-power factor helps achieve a safe and sustainable energy source that is free of any interruptions in the electrical power supply by reducing losses in the electricity networks and improving its efficacy.
As shown in Figure 1, the overall general flow of the purposed system for power factor correction is presented. System input and outputs are clarified, where the microcontroller severs as an interface platform for the captured values from the sensors and activates the output relays modules based on the outcomes from the Matlab/Simulink proposed model.

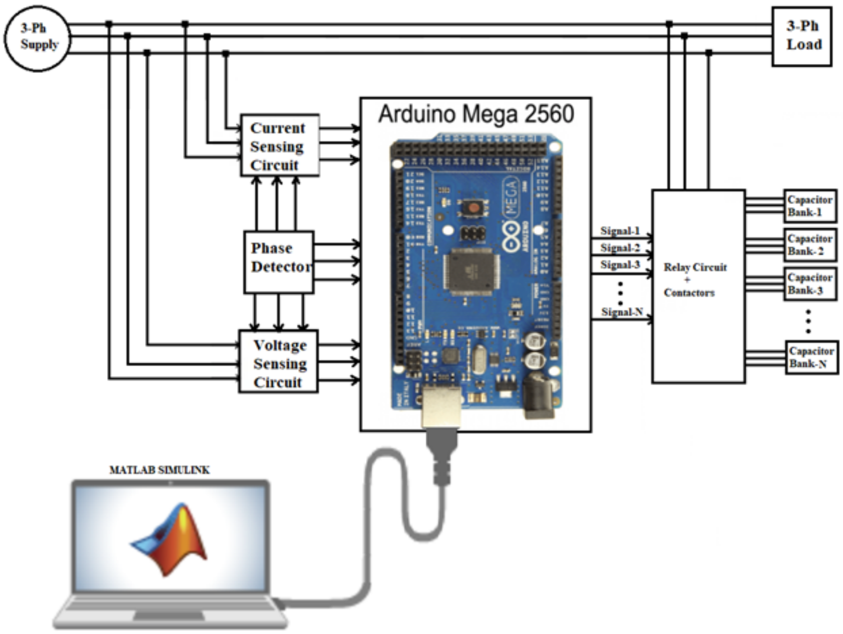


Figure 1: Purposed system general flow.

2. METHODOLOGY

In this study, a simulation will be developed in MATLAB to ascertain the most effective capacitor configuration for achieving the intended power factor. Additionally, phase, current, and voltage measurements will be implemented to mitigate variations during capacitor switching and resolve prevalent contactor switching issues.
The overall block diagram is split into two parts; the first part is the MATLAB Simulink software with Arduino support package which is presented in (Figure 1). The Simulink diagram consists of voltage, current, and phase measurement blocks as it is responsible for the connection process with the Simulink program with Arduino mega. The captured measurements are required for

optimization algorithm to determine the optimum combination of capacitors to improve the power factor to a predetermined value. In addition, the optimization algorithm used to determine the optimal combination and best (connect/disconnect) sequence to mitigate variations during capacitor switching. The second part of this investigation consists of actual measurements sensors with assistance of current transformers, voltage transformers, and phase detecting circuits. These sensors are used in order to measure line values immediately prior to and following correction. The measurement data are then sent to a microcontroller, which in turn passes it to the Simulink to make the decision through the optimization algorithm. After that the decision is returned through the controller to the separation devices (relays module), which give the command to the contactor to disconnect or connect the capacitors stages. To calculate the required capacitance, Figure 2 shows the measurement of voltage, current and phase shift for each phase. From these values the active power (P) is then calculated by formula (1):

$$P = V_{Ph} \times I \times \cos\phi o \qquad (1)$$

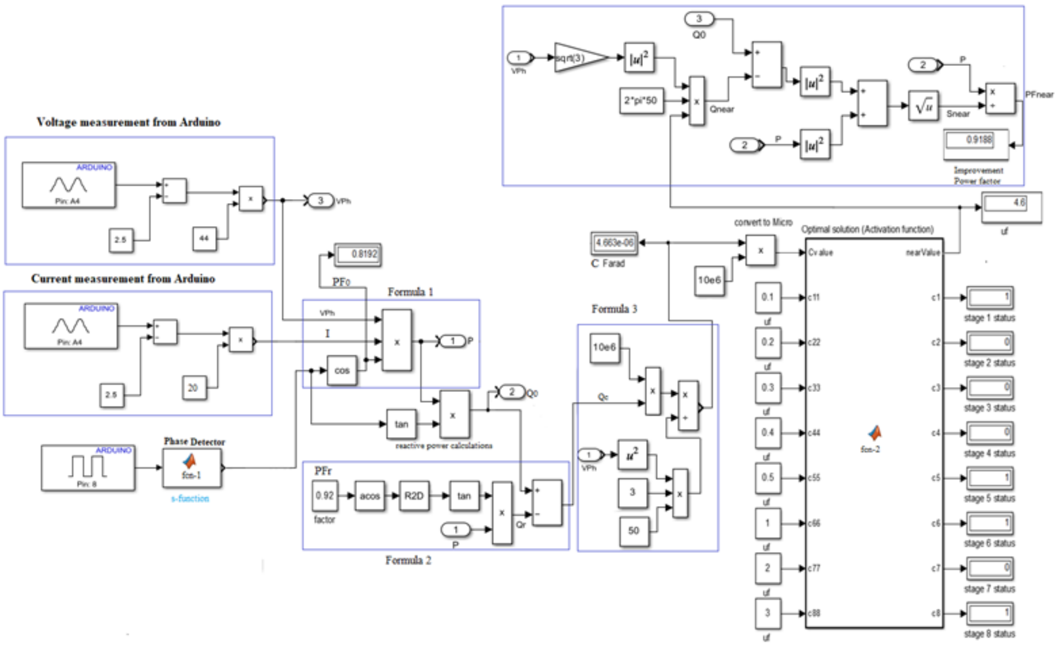


Figure 2: MATLAB simulink optimal solution model.

To determine the required capacitance the Microcontroller calculates the capacitive power (Qc) necessary to improve the power factor of the three phase to 0.92 (PFr) by using the formula (2):

$$Qc = Qo - Qr = P\left(\tan(\phi o) - \tan(\phi r)\right) \qquad (2)$$

Where: (Qc) is the required capacitive power, (Qo) is the reactive power when PF=PFo, (Qr) is the reactive power when PF=PFr.

And then the value of the three capacitors can be computed by the formula (3):

$$C = \frac{Qc.10^{6}\left(\mu F\right)}{3.W.V^{2}} \qquad (3)$$

Where: C: is the required capacitive value, V: is the voltage, W: is 2π x frequency.

2.1. Improvement techniques for PFC

2.1.1. Check and modify method

At the beginning, the common way to improve the power factor value in power system is (check and modify), the principle in sequence operations of the stages -adding or removing capacitor stage- based on compare with current power factor value only as shown in Figure 3.

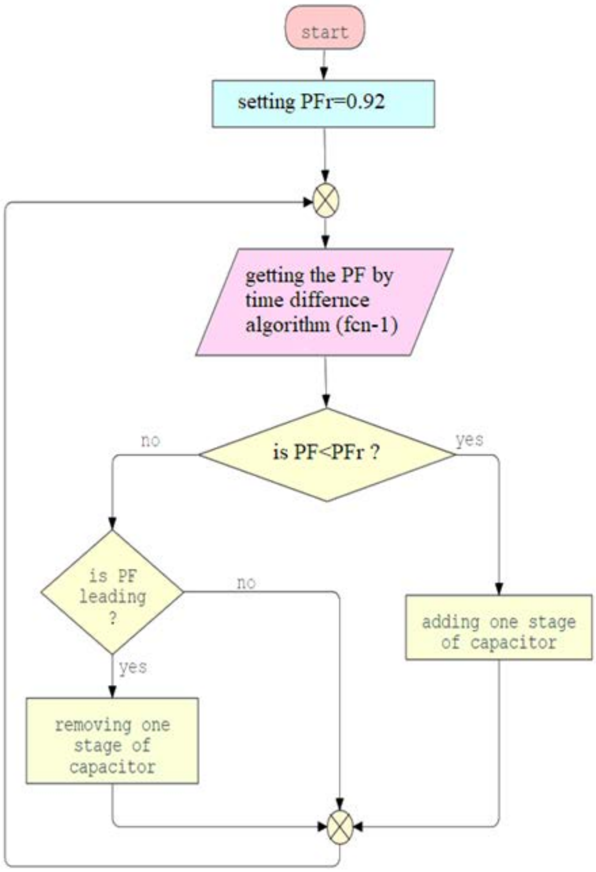


Figure 3: General (check and modify) algorithm.

It is clear that this algorithm performs several erroneous experiments before reaching the acceptable result, because it deals with the current value of the power factor and can't predict what the value will be before the response process. This gives it a lot of weaknesses compared with the algorithm based on the optimal solution as will be discussed in the next section.

2.1.2. Optimal solution method

The initial stage is to identify the optimal solution, as illustrated in Figure 4.

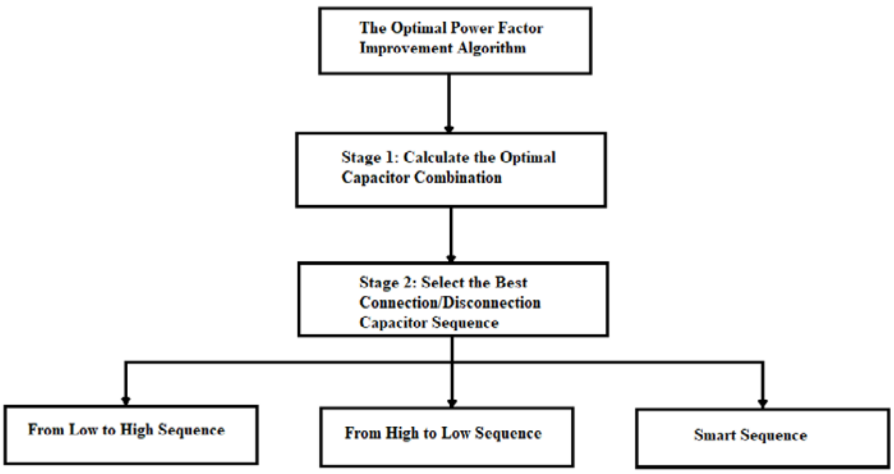


Figure 4: Identify optimal solution process.

Subsequently, the optimal sequence for achieving the desired power factor value is determined which is very important to avoid switching related issues and reduce the number of contactor switching times. In the optimal solution algorithm, as illustrated in Figure 5, the focus is on all the quantities of the power system such as voltages and currents. Then, these quantities are used enter in the power equations to find the apparent power which composed from the real and reactive power in addition to determining the value of the power factor. Then calculate the value of the exact theoretical capacitance capable of adjusting the value of the power factor to the required value.

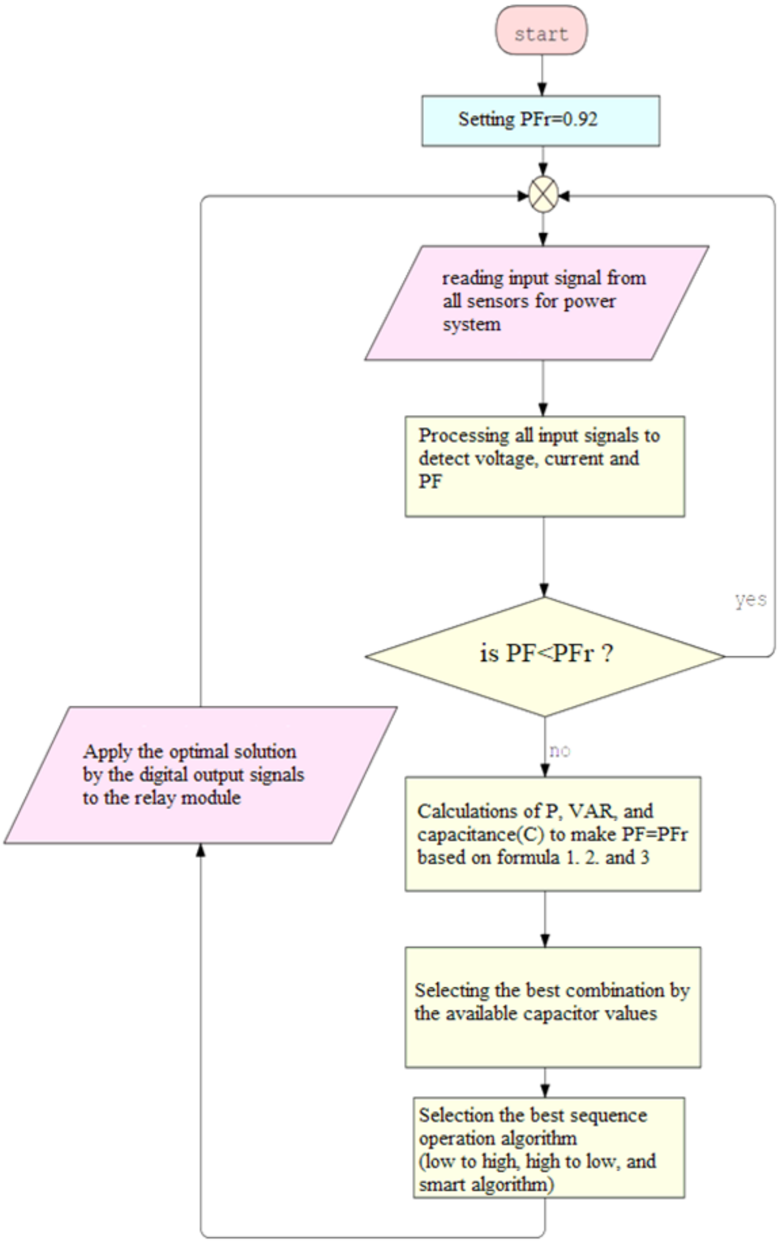


Figure 5: Optimal solution algorithm.

It is common for the theoretical value to not be available with the necessary accuracy due to the practical values of capacitors. Consequently, the subsequent step is to determine the optimal combination of available capacitors to achieve the closest target value. And because there must be time differences between the connection or disconnection of capacitors from the load bus and to ensure the highest level of stability, different algorithms developed for operation techniques that are capable of determining the optimal sequence in which to employ the chosen solution.

3. SYSTEM DESIGN

For the purpose of effectively simulating the algorithms, the power optimization system that has been proposed needs to be constructed in an integrated manner. As depicted in Figure 6, the input and output devices were constructed and attached to the microcontroller. Each device was connected to the microcontroller in its designated location.

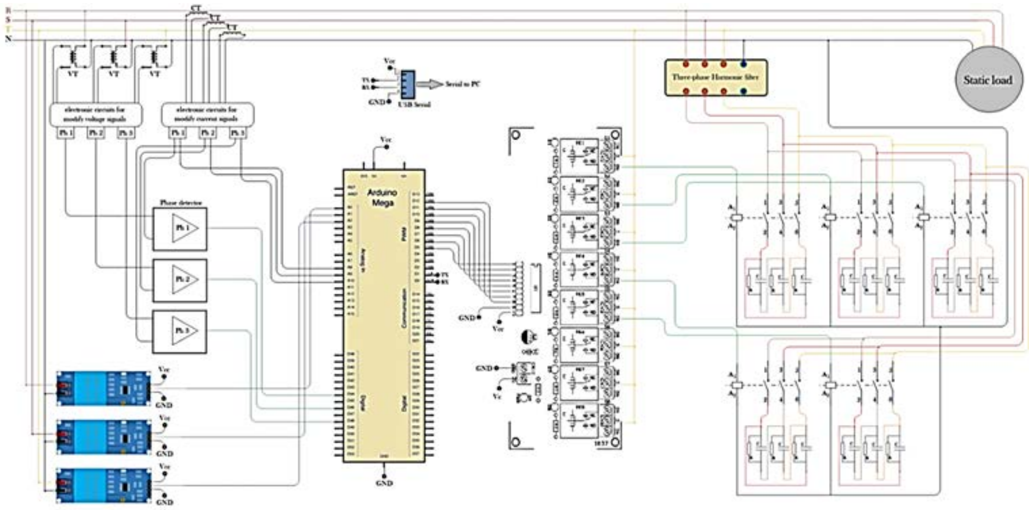


Figure 6: Schematic design & measurement.

3.1. Arduino Microcontroller

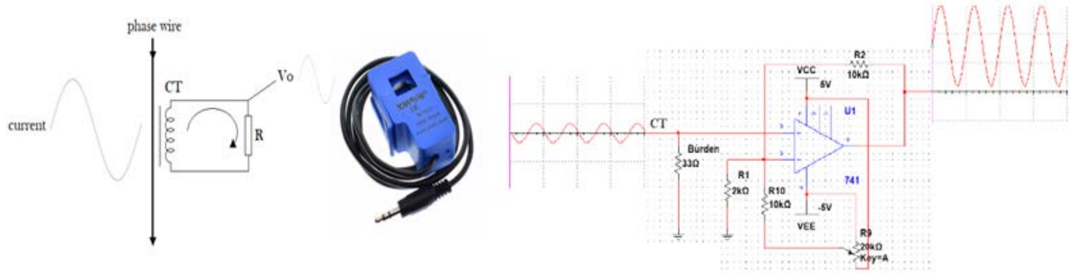
The purposed design involves a microcontroller that is capable of operating at a high level of efficiency due to the substantial volume of data that requires processing and decision-making. Therefore, the "Arduino Mega" is employed due to its high number of analog pins and the aforementioned specifications, which provide greater flexibility in the event of pin damage. Its primary function is to obtain the various readings from the voltage and current sensors, calculate the phase shift angle, and process the data. This information is then incorporated into the various power equations to determine the capacitance value necessary to enhance the power factor to the desired level. The Arduino Mega 2560 is a microcontroller board that is based on the ATmega2560.

3.2. Measurement components

The focus will be on measurement devices used to calculate electrical quantities, such as voltages, currents and phase shift angle. All of these quantities are sent to the microcontroller which it processing them and finding different power types, as active, reactive and apparent power.

3.2.1. Current measurement

This circuit is designed to amplify the wave applied to the Burden resistor, which is directly proportional to the current value, because the conversion rate in the current transformer 'SCT013' is 100 - 0.050A, and the applied voltages will be very small at the low values of current as shown in (Figure 7a). The outcome wave will be sent to the comparator circuit for phase measurement.



(a) (b)

Figure 7: (a) current transformer, (b) Amplification circuit on 2.5 volts dc level.

This circuit is designed to amplify and add 2.5 volts as a DC level on the wave applied to the Burden resistor as shown in (Figure 7b), because this outcome wave will send to analog input pin in microcontroller, and the analog pin will not recognize on negative side of sensor wave.

3.2.2. Voltage measurement

The sensor ZMPT101B module has a high ability to isolate the high voltage side from the small voltage side, the sensor measures the input voltage of 0 - 250 volts AC and converts it to a voltage output of 0 - 5 volts AC raised at the level of 2.5 DC voltage. So, we can directly send the resulting wave to the analog input of the microcontroller without negative side, small voltage is directly proportional to the voltage in the high side. The ZMPT101B sensor module is illustrated as in Figure 8.

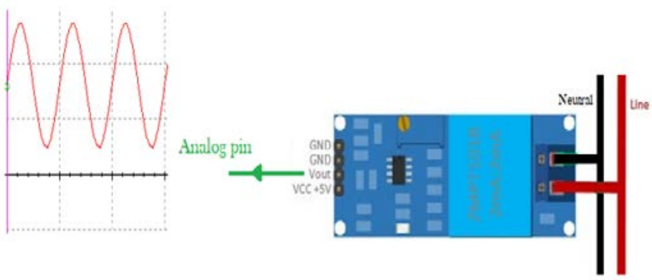


Figure 8: Voltage sensor ZMPT101B connection.

3.2.3. Voltage phase measurement

The main objective of this circuit design is to obtain the true voltage waveform with reduction the value of the wave to a small value to be within the limits of reading the comparator circuit as shown in Figure 9. The outcome wave will be sent to the comparator circuit for phase measurement.

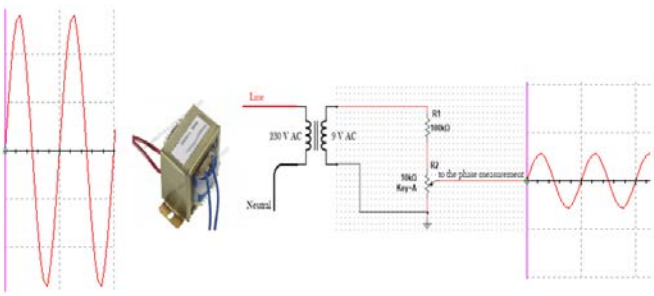


Figure 9: Voltage divider technique with voltage transformer.

3.2.4. Determine phase shift angle

In the circuit shown in Figure 10 there is a 'XOR' logical gate, which calculates the difference between two logical signals in the form of giving two logical level ‘1’ and ‘0’ from comparator circuit.

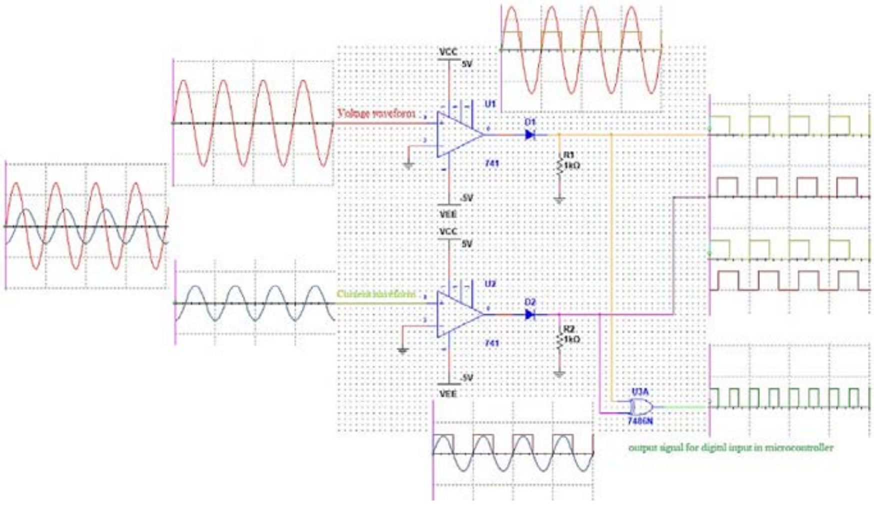


Figure 10: Comparator circuits with XOR logical gate.

The logic value 1 is given when the two incoming waves are different, so the time given to this value will be 5V, which expresses the time difference between the voltage and current wave. This signal will be sent to the input digital pin in the microcontroller to calculate this time based on an algorithm that designed specifically for it.

3.2.5. Phase detector algorithm

This algorithm uses the XOR output pulse signal which is received from the digital pin of the microcontroller to determine the angle between voltage and current which is used to calculate the power factor value as shown in Figure 11.

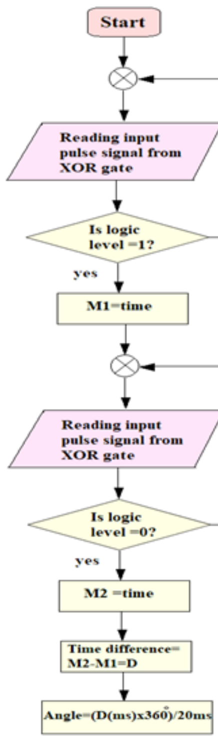


Figure 11: Phase detector algorithm.

3.3. Relay module

This item is used for the digital output process that follows the solution imposed by the microcontroller. This tool is able to separate the small control voltages 5V DC from the Arduino and the large control voltages 230V AC used to activate the contactors. (Figure 12) shows a structure of relay module. This module contains 8 channels of the main relay unit with protection elements.

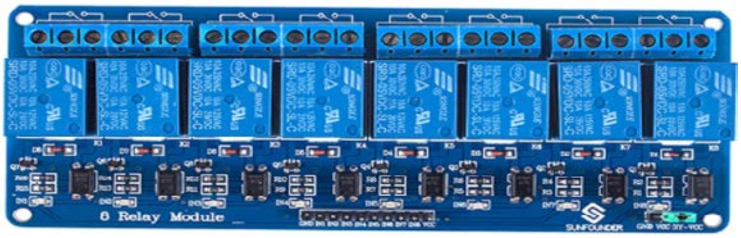


Figure 12: The Relay module.

3.4. Contactors

The three-phase contactors are shown in (Figure 13) is for control the three-phase capacitors removal or addition of loads attached to its contacts through an activation signal 230V AC from the relay model which was explained previously.

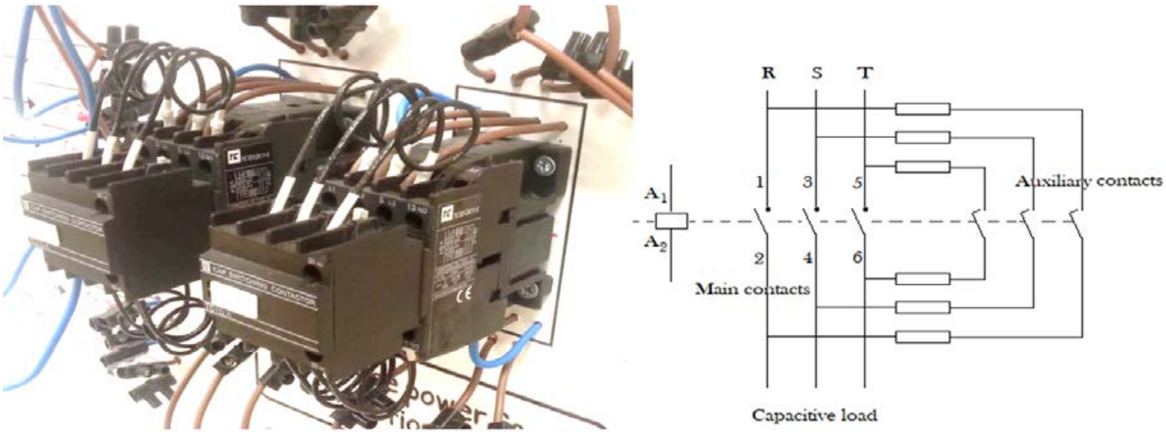


Figure 13: Contactors 230 V AC activation signal.

This device consists of three main contacts normally open, and three auxiliary contacts that follow the main contacts movement during interruption and connection. These contacts are designed to withstand small wire resistors.

3.5. Capacitors

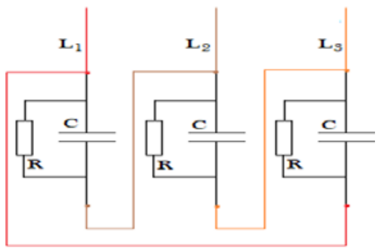


Figure 14: Delta capacitors connection with discharging resistors.

The main function of this electrical component is to compensate value of reactive power.
When connected to the electrical grid, it will provide a reactive power value, which improves

the power factor value. To be ready to connect with the three-phase electric grid, we make a configuration as shown in (Figure 14).

When the contactor interrupts a capacitor during operation, the capacitor will be carrying a high value of voltage on its terminals. It will take relatively long time to be discharged before the second connection, which may cause a dangerous electrical spark affecting on the system parts such as the contactor. So, we can use a discharge resistor as shown in (Figure 15) to speed up the discharge process within a few seconds.

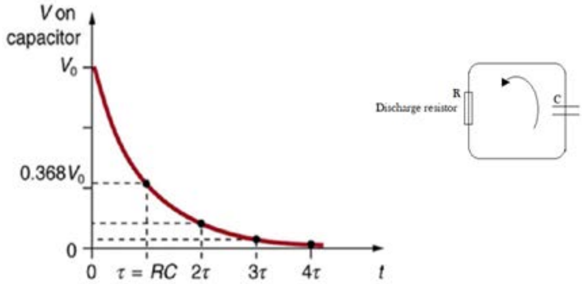


Figure 15: Capacitor discharging behavior through discharging resistor.

Assuming that the applied value of the voltage was 400 volts after interruption, we will track the voltage change over time when adding 100kΩ (2W) as a discharge resistor: the results will be as shown in (Table 1)

Table 1: Discharging 400 volts after interruption.

	1τ	2τ	3τ	4τ	5τ
Any µF value	147.12 V	54.12 V	19.88 V	7.32 V	2.69 V

And the maximum value of capacitance in this project is 16 µF, so the maximum value of τ is 1.6 second, and the full discharge time is 8 second.

3.6. Three phase AC power supply

The three phase AC power supply shown as in Figure 16. It is composed of a three-phase transformer voltage which has conversion rate of 1:1. It provides the system with a three-phase power source. The primary advantage of its utilization is to offer electromagnetic insulation for the principal electrical grid.

Figure 16: Three phase AC power supply.

3.7 Static load

This laboratory device shown in (Figure 17) is used to replace the inductive loads with an additional active power value, depending on the sets of resistors and inductors whose value is controlled by the user without need to use a real motor as example. The resistor box consists of three phase each phase has 3 loads (R1=180Ω, R2=360Ω, R3=720Ω) and the inductive load also has three phase loads each one has (L1=570mH, L2=1140mH, L3=2280mH). For example, for load (R1 L1 L3) this mean the resistive load set to (R1=180Ω, R1=180Ω, R1=180Ω) and connected parallel with inductive load (570mH//2280mH, 570mH//2280mH, 570mH//2280mH).

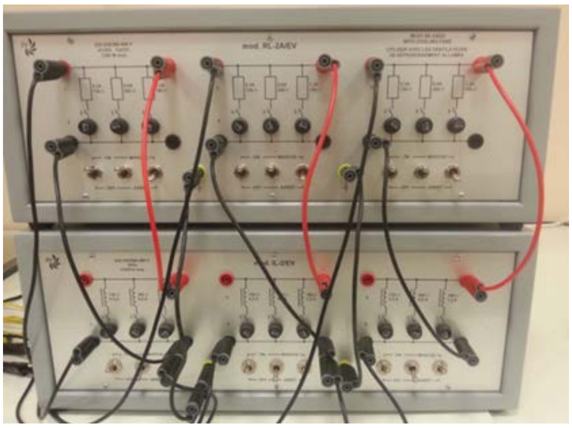


Figure 17: Static load.

As shown in Figure 18, the overall assembled power factor system is realized. The assembly was made on illustrated board to be suitable for lab educational purposes.

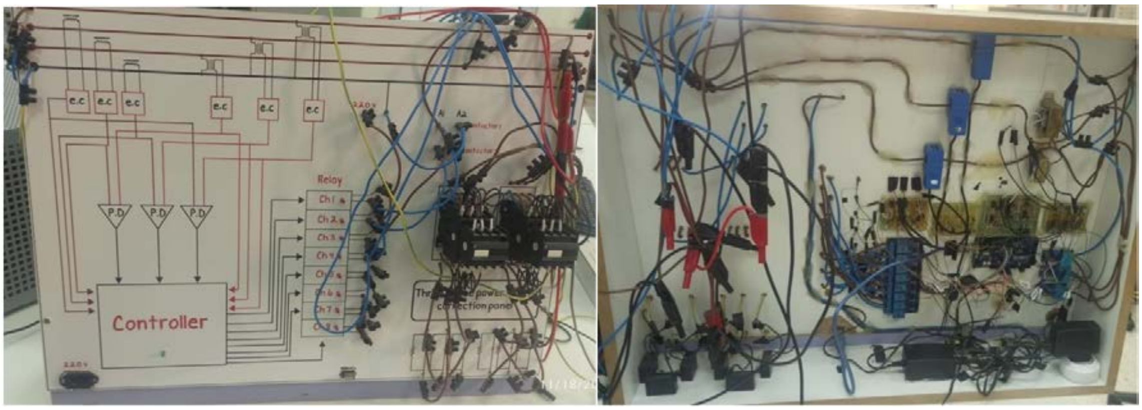


Figure 18: The overall developed PFC system.

4. ALGORITHMS FOR PROCESSING

4.1. Getting the best Combination

After reaching the theoretical capacitance value which capable of improving the power factor to the required value. The principle of this process is selecting the best combination of available capacitor stages to obtain the nearest practical value to the calculated theoretical value as the power system equations outcomes (Figure 19).

4.2. Operation Techniques (to determine the best sequence)

All the algorithms used in operation techniques (sequence) that are capable of activating or deactivating of capacitor stages selected according to the previous selecting algorithm, all these algorithms depend on operation state of previous case as a starting point for the next case (see Figure 20).

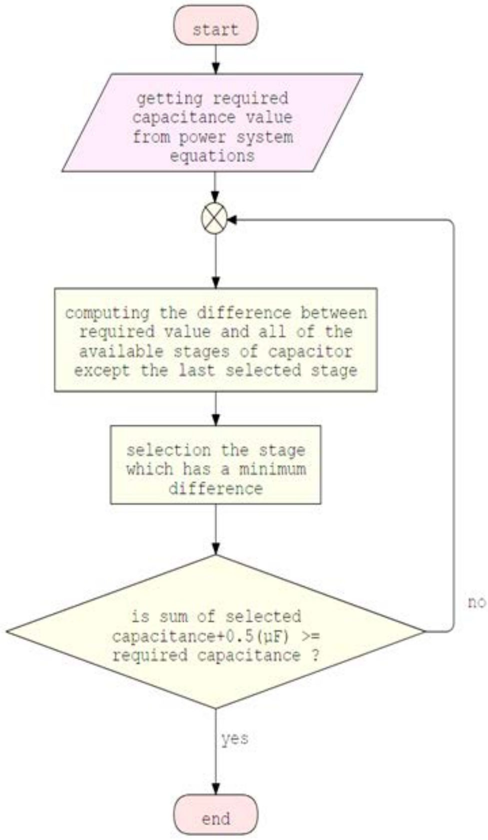


Figure 19: Getting optimal combination algorithm.

Figure 20: Available capacitor stages.

A. Comparison with Previous Case (from low to high):

In this algorithm the sequence operation of the stages based on finding the least difference in any activating or deactivating process compared to the previous value or from smallest to largest capacitor value, whether activating or deactivating process (Figure 21).

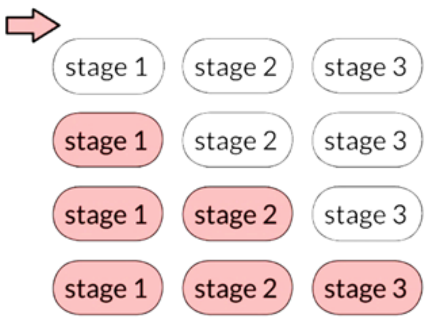


Figure 21: Low to high sequence algorithm.

B. Descending (from high to low):

In this algorithm the sequence operation of the stages from largest to smallest capacitor value, whether activating or deactivating process (Figure 22).

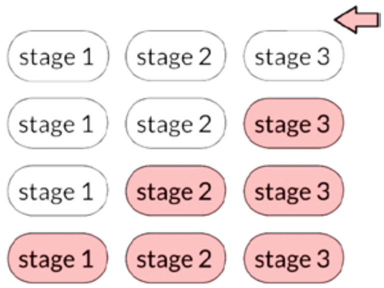


Figure 22: High to low sequence algorithm.

C. Comparison with Subsequent Case (smart algorithm):

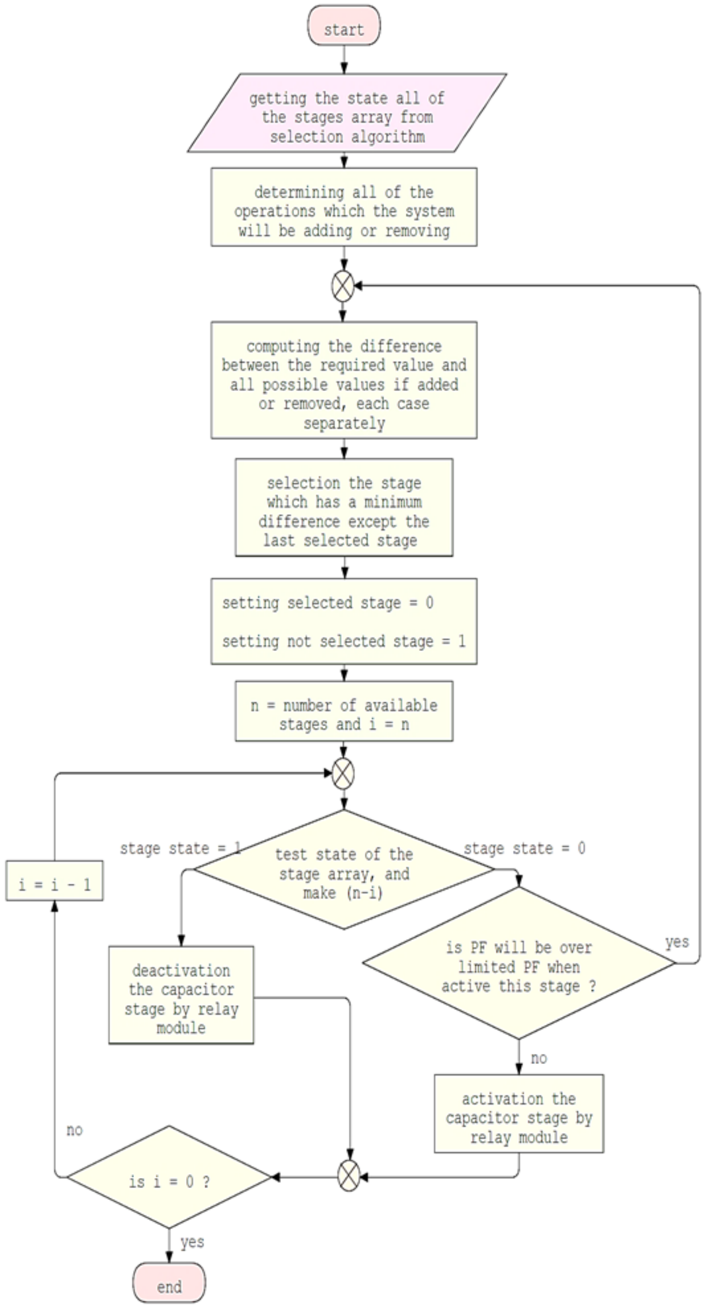


Figure 23: Smart algorithm.

In this proposed algorithm (Figure 23) the sequence operation of the stages based on finding the

least difference in any activating or deactivating process compared to the subsequent value (it will be apply).
This algorithm is always able to stay close to the target value during processing until reaching the final value. Moreover, this algorithm is characterized by its ability not to reach over-correction case during processing for applying the target capacitance value by adding a question before the activation process for any value of capacitor stage that was chosen according to the basic principle of this algorithm.

5. RESULTS AND DISCUSSIONS

In this section, a case study is analyzed to examine the proposed optimal solution algorithm and illustrate the results of power factor correction experiments which applied on the laboratory load. Suppose that [R1, R2, R3] is the resistive part of the load and [L1, L2, L3] is the inductive part. (Table 2) and (Table 3) shows the measurements on three phase user line before and after power factor correction with delta connected capacitors for [R1, L1, L2]:

Table 2: Before power factor correction (BPFC).

Voltage (v)	Current (A)	Reactive power (VAR)	Active power (w)	Power factor	Required VAR	Required Micro farad
413	1.09	711.19	319.7	0.41	575	3.58

Table 3: After power factor correction (APFC).

Voltage (v)	Current (A)	Reactive power (VAR)	Active power (w)	Power factor
412	0.49	133	322.6	0.925

Table 4 illustrates the measured performance of the proposed power factor correction (PFC) system for various load combinations.
The table compares the power factor before (BPFC) and after (APFC) correction, the associated reactive power (VAR), and the requisite capacitance (μF) to achieve the desired improvement in each case.
The results illustrate the effectiveness of the optimal capacitor selection and control strategy by exhibiting a substantial increase in power factor across all load scenarios, as well as a substantial decrease in reactive power.

Table 4: Measurements for various combination of load.

Load combination	VAR BPFC	VAR required	μF required	VAR APFC	PF BPFC	PF APFC
R1 L1 L3	1127.1	1018.74	6.15	126.1	0.22	0.915
R2 L1 L2	710	477.2	3	243	0.61	0.981
R2 L1 L3	1175	920.6	5.79	271	0.44	0.91
R3 L1 L2	649.6	203.1	1.23	485.8	0.85	0.91
R1 R2 L2 L3	1432	1107	6.78	382	0.47	0.91

As illustrated in Figure 24, an illustrative plotted chart that displays both the improvement in power factor (represented by bars) and the reduction in reactive power (represented by lines) for each load combination in Table 4 is presented.

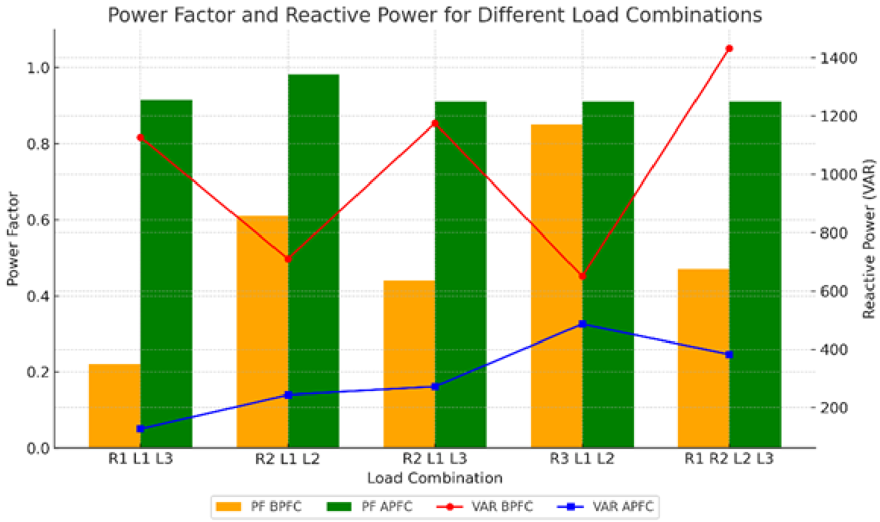


Figure 24: Combination of loads power factor and reactive power.

Relay module consists of 8 channels (the expression Ch1 related to "channel 1" and so on). Each channel sends activation signal to contactor which connected to delta connected capacitors. (Table 5) shows the number of module channel and the corresponding value of capacitor:

Table 5: Values of available capacitor stages.

Number of module channel	Value of capacitor (µF)
1	1
2	2
3	4
4	8
5	16

In practical applications of industry, the loads of factory changing from period of time to another in the same day according to required load to complete the tasks in each period. So that the power factor correction system must be capable to improve the power factor for a dynamic load. (Table 6) shows the first scenario of changing the combination of the laboratory load at three different times which requires three power factor correction operations. Moreover, it illustrates the decision of microcontroller and basic measurement in each combination.

Table 6: First scenario of changing load.

Load	PF	µF required	VAR required	Decision	Number of PFC operation	PF after PFC
R1 R2 L1 L2	0.74	2.3	375.4	Ch2 on	1	0.910
R1 R2 L1 L2 L3	0.55	5.92	939.9	Ch2 off Ch4 on	2	0.909
R2 L1 L2 L3	0.83	0.98	155.4	Ch1 on Ch4 stay	3	0.901

The sequence of inserting or removing capacitors may based on four different operation technique mentioned before, (Table 7) shows the sequence until the third correction for the previous scenario. Note that PFC1 represent the first power factor correction and so on.

Table 7: Sequence until the third correction for the first scenario.

Operation technique	PFC1	PFC2	PFC3
From low to high	Ch2 on	Ch2 off Ch4 on	Ch1 on Ch4 stay on
From high to low	Ch2 on	Ch4 on Ch2 off	Ch4 stay on Ch1 on
Smart algorithm	Ch2 on	Ch4 on Ch2 off	Ch4 stay on Ch1 on
Check and modify	Ch1 on Ch2 on Ch1 off	Ch1 on Ch2 stay on Ch3 on Ch4 on Ch1 off Ch2 off Ch3 off	Ch1 on Ch4 stay on

(Table 8) illustrate a comparison between the first three operations algorithm and the common way (check and modify algorithm) in number of contactor switching for the previous scenario:

Table 8: Number of contactors switching for the first scenario.

Operations algorithm	The first three operations algorithm	Check and modify algorithm
Number of contactor switching	4	10

5.1. Refer to previous scenario:

For the first power factor correction operation (PFC1), there is one action which is switching on channel 2, thus, there is no difference between applying any one of the first three operation algorithms.

For the second power factor correction operation (PFC2), “from high to low” and “smart” operations have the same decision which is switching channel 4 on then switch channel 2 off. This is absolutely better than “from low to high” operation which switch channel 2 off then switch channel 4 on. For the third power factor correction (PFC3), there is no difference in the four operations because there is one action.

Table 9 shows the power factor correction (PFC) system’s operation in the second scenario of changing load conditions.

The findings show that the controller efficiently enhanced power factor by connecting/ disconnecting capacitors in response to load demands. The system consistently operates steadily and effectively, achieving a post-correction PF of 0.90 or higher.

The system’s flexibility in choosing the best capacitor banks demonstrated that the number of PFC operations varies based on the load combination.

Furthermore, the system can compensate for excess reactive power (negative VAR) in specific scenarios, like the third case, avoiding overcorrection. Overall, the proposed strategy in maintaining acceptable power factor levels under fluctuating load scenarios.

Table 9: Second scenario of changing load.

Load	PF	μF required	VAR required	Decision	Number of PFC operation	PF after PFC
R1 R2 L1 L3	0.57	5.14	822.4	Ch1 on Ch3 on	1	0.903
R1 R2 L1 L2 L3	0.71	3.05	787.4	Ch1 off Ch3 off Ch4 on	2	0.904
R3 R2 L1 L2 L3	0.90	-1.73	-275	Ch2 on Ch3 on Ch4 off	3	0.916

(Table 10) shows the sequence of inserting and removing capacitors for the second scenario for various operation technique until the third correction for the second scenario.

Table 10: Sequence until the third correction for the second scenario.

Operation technique	PFC1	PFC2	PFC3
From low to high	Ch1 on Ch3 on	Ch1 off Ch3 off Ch4 on	Ch 2 on Ch3 on Ch4 off
From high to low	Ch3 on Ch1 on	Ch4 on Ch3 off Ch1 off	Ch4 off Ch3 on Ch 2 on
Smart algorithm	Ch3 on Ch1 on	Ch1 off Ch4 on Ch3 off	Ch4 off Ch3 on Ch 2 on
Check and modify	Ch1 on Ch2 on Ch3 on Ch2 off	Ch2 on Ch4 on Ch1 off Ch2 off Ch3 off	Ch4 off Ch1 on Ch2 on Ch3 on Ch1 off

(Table 11) illustrate a comparison in number of the contactor switching for the second scenario between the first three operations algorithm and check and modify algorithm:

Table 11: Number of the contactor switching for the second scenario.

Operations algorithm	The first three operations algorithm	Check and modify algorithm
Number of the contactor switching	8	14

5.2. Refer to the second scenario:

For (PFC1), if "low to high" operation is applied, the sequence will be (Ch1 on → Ch3 on) while if each of "from high to low", "smart" operations are applied the sequence will be (Ch3 on → Ch1 on), thus, the best sequence is when applying "from low to high" because it will add the capacitors ascending which reduce result in the least transient.

For (PFC2), the best sequence for this case is when applying "smart" operation because it will be (Ch1 off → Ch4 on → Ch3 off). while in "from high to low" operation the sequence will be (Ch4 on → Ch3 off → Ch1 off), and in "from low to high" operation the sequence will be (Ch1 off → Ch3 off → Ch4 on), which cause more transient than the first operation.

For (PFC3), the best sequence for this case is when applying “smart” or “from high to low” operation because it will be (Ch4 off → Ch3 on → Ch2 on). while in “from low to high” operation the sequence will be (Ch2 on → Ch3 on → Ch4 off), and in “smart “ operation the sequence will be (Ch2 on → Ch4 off → Ch3 on), which cause clearly over correction than the first operation. (Table 12) shows the third scenario of changing the combination of the laboratory load:

Table 12: Third scenario of changing load.

Load	PF	µF required	VAR required	Decision	Number of PFC operation	PF after PFC
R1R2R3L2 L3	0.78	4.1	656.4	Ch3 on	1	0.919
R1R3L2L3	0.86	1.36	216.7	Ch3 stay Ch1 on	2	0.908
R1R3L1L2L3	0.84	1.83	292	Ch3 stay Ch2 on Ch1 stay	3	0.926

(Table 13) shows the sequence of inserting and removing capacitors for the third scenario:

Table 13: Sequence until the third correction for the third scenario.

Operation technique	PFC1	PFC2	PFC3
From low to high	Ch3 on	Ch1 on Ch3 stay	Ch 1 stay Ch2 on Ch3 stay
From high to low	Ch3 on	Ch3 stay Ch1 on	Ch3 stay Ch2 on Ch 1 stay
Smart algorithm	Ch3 on	Ch3 stay Ch1 on	Ch3 stay Ch2 on Ch 1 stay
Check and modify	Ch1 on Ch2 on Ch3 on Ch2 off Ch1 off	Ch1 on Ch3 stay	Ch4 off Ch 1 stay Ch2 on Ch3 stay

(Table 14) illustrate a comparison in number of contactors switching for the third scenario between the first three operations algorithm and check and modify algorithm:

Table 14: Number of contactor switching for the third scenario.

Operations algorithm	The first three operations algorithm	Check and modify algorithm
Number of contactor switching	3	7

5.3. Refer to the third scenario:

For (PFC1), there is one action which is switching on channel 3, thus, there is no difference between applying any one of the operation algorithms. For (PFC2), there is one action which is switching on channel 1, thus, there is no difference between applying any one of the operation algorithms. For (PFC3), there is no difference in the four operation algorithms because there is one action.

6. CONCLUSION

This study discusses the development and implementation of a three-phase automatic centralized power factor correction panel, with capacitors arranged in a configuration where one is double the other, based on an optimal solution methodology. The proposed design aims to enhance the system's performance and reliability by extending the lifetime of contactors through a reduced frequency of switching operations compared to the stage technique (check and modify). Results shows that minimum difference in number of switching decision is 4 for different cases until the third power factor correction process. Moreover, it results in the least possible transient due to using different operation techniques which offers the best sequence of addition or remove capacitors. Results had shown that in each scenario the optimal algorithm had successfully able to determine the optimal of the required capacitor to reach the predetermined power factor value. Therefore, the proposed sequence process proven to reduce the number of contactors switching. It is noticed that the relative error in the project is due to four types of error which are: approximation is required for capacitor value because there isn't 0.5μF available in the markets, unbalance three phase, error related to the accuracy of measurement devices and that the load of each phase is not exactly equally with the other phases.

Author Contributions: Author Contributions: Dreidy, Safarini: Conceptualization; Dreidy, . Salah, Safarini: methodology, formal analysis, writing—original draft preparation, validation; Dreidy, Salah: review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: The authors have not disclosed any funding.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare that they have no conflict of interest.

Acknowledgment: The authors are grateful to Palestine Technical University - Kadoorie for their financial support to conduct this research.

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