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CHAPTER I

INTRODUCTION TO POWER FACTOR & POWER QUALITY

1.1 GENERAL OVERVIEW

1.1.1 Definition of Power Factor:

In electrical engineering, the power factor of an AC electrical power system is defined as the ratio of the real power absorbed by the load to the apparent power flowing in the circuit, and is a dimensionless number in the closed interval of $-1$ to $1$. A power factor of less than one indicates the voltage and current are not in phase, reducing the instantaneous product of the two. Real power is the instantaneous product of voltage and current and represents the capacity of the electricity for performing work. Apparent power is the average product of current and voltage. Due to energy stored in the load and returned to the source, or due to a non-linear load that distorts the wave shape of the current drawn from the source, the apparent power may be greater than the real power. A negative power factor occurs when the device (which is normally the load) generates power, which then flows back towards the source.

In an electric power system, a load with a low power factor draws more current than a load with a high power factor for the same amount of useful power transferred. The higher currents increase the energy lost in the distribution system, and require larger wires and other equipment. Because of the costs of larger equipment and wasted energy, electrical utilities
will usually charge a higher cost to industrial or commercial customers where there is a low power factor.

1.1.2 Definition of Power Factor Correction:
The power factor correction means bringing the power factor of an AC circuit nearer to one by using the equipment which absorbs or supply the reactive power to the circuit. Usually, the power factor correction can be done by using the capacitor and the synchronous motor in the circuit. The power factor correction will not change the amount of true power, but it will reduce the apparent power and the total current drawn from the load.
The phase shift between the voltage and the current of the circuit is known as the power factor. It is represented by the cosine of the angle $\phi$. The power factor represents the fraction of total energy use for doing useful work, and the remaining energy is stored in the form of magnetic energy in the inductor and capacitor of the circuit.
The most economical value of power factor lies between 0.9 to 0.95. If the value of power factor lies below 0.8 (approx.), then it draws more current from the load. The large current increases the losses and requires a large conductor, thus increases the cost of the system. The loss can be reduced by correcting the power factor of the system.
If $\phi$ is the phase angle between the current and voltage, then the power factor is equal to the cosine of the angle $\cos \phi$ (Figure 1)

\[ P = |s| \cos \phi \]

Figure (1): AC power triangle
The power factor is defined as:
\[ p.f = \cos \varphi = \frac{P}{S} \]
In the case of a perfectly sinusoidal waveform, P, Q and S can be expressed as vectors that form a power triangle such that:
\[ S^2 = P^2 + Q^2 \]

**Compensation of Power Factor:**

Power factor correction is simply defined as shown in Figure 2:

(1) **Before correction:**

\[ Q_L = Q_{L1} , \quad S = S_1 , \quad \varphi = \varphi \]

(2) **After correction by add capacitor:**

\[ Q_L = Q_{L2} , \quad S = S_2 , \quad \varphi = \varphi_2 \]
\[ \varphi_2 < \varphi_1 \]
Then P.F_2 > P.F_1 correction
\[ Q_c = Q_{L1} - Q_{L2} \]
\[ \tan \varphi_1 = \frac{Q_{c1}}{P_L} \]
\[ Q_{L1} = P_L \tan \varphi_1 \]
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\[ Q_{L2} = P_L \tan \varphi_2 \]
\[ \tan \varphi_2 = \frac{Q_{L2}}{P_L} \]

**Size of capacitor bank:**

\[
\begin{align*}
Q_c &= P_L \left( \tan \varphi_1 - \tan \varphi_2 \right) \\
\omega_c &= \frac{Q_c}{w^2} \\
Q_c &= \frac{v^2}{\omega_c} = wc v^2 \text{ ‘Farad’}
\end{align*}
\]

1.1.3 **Definitions of Power Quality**

There are different definitions for power quality.

1. According to Utility, power quality is reliability.
2. According to load aspect, it is defined as the power supplied for satisfactory performance of all equipment i.e., all sensitive equipment.
3. This depends upon the end user. According to end user point of view, it is defined as, “any power problem manifested in voltage, current, or frequency deviations that result in failure or disoperation of customer equipment”
4. In IEEE dictionary, power quality is defined as “the concept of powering and grounding sensitive equipment in a matter that is suitable to the operation of that equipment”.
5. IEC (International Electrotechnical Commission), it is defined as, “set of parameters defining the properties of the power supply as delivered to the user in normal operating conditions in terms of continuity of supply and characteristics of voltage (magnitude, frequency, waveform).

The power supply system can only control the quality of the voltage; it has no control over the currents that particular loads might draw. Therefore, the standards in the power quality are related to maintaining the supply voltage within certain limits.

Power quality determines the fitness of electrical power to consumer devices. Synchronization of the voltage frequency and phase allows electrical systems to function in their intended manner without significant loss of performance or life. The term is used to describe electric
power that drives an electrical load and the load's ability to function properly. Without the
proper power, an electrical device (or load) may malfunction, fail prematurely or not operate
at all. There are many ways in which electric power can be of poor quality and many more
causes of such poor quality power.

1.1.4 Why Power Quality Is Important?

Along with technology advance, the organization of the worldwide economy has evolved
towards globalization and the profit margins of many activities tend to decrease. The
increased sensitivity of the vast majority of processes (industrial, services and even
residential) to power quality problems turns the availability of electric power with quality a
crucial factor for competitiveness in every activity sector. The most critical areas are the
continuous process industry and the information technology services. The performance of
electrical devices is directly linked to the power quality level. Quality phenomenon or power
quality disturbance can be defined as the deviation of the voltage and the current from its
ideal waveform. Faults at either the transmission or distribution level may cause voltage sag
or swell in the entire system or a large part of it. Also, under heavy load conditions, a
significant voltage drop may occur in the system. Voltage sag and swell can cause sensitive
equipment to fail, shutdown and create a large current unbalance. These effects can incur a
lot of expensive from the customer and cause equipment damage. So, in order to provide
uninterrupted power to the service sectors as well as others for economic growth and prevent
equipment damage with varying voltage level and frequency, undoubtedly power quality
improvement is utmost important.
1.1.5 **Power Quality Problems and Effect:**
There are several aspects of power quality problems due to which an electrical device may malfunction, fail prematurely or not operate at all. Some of the most common power supply problems and their likely effect on sensitive equipment.

1) **Voltage Dips and Under Voltage**

Voltage dips are brief reductions in voltage, typically lasting from a cycle to a second or so, or tens of milliseconds to hundreds of milliseconds. Voltage swells are brief increases in voltage over the same time range. Longer periods of low or high voltage are referred to as “under-voltage” or “overvoltage”.

Voltage dips are caused by abrupt increases in loads such as short circuits or faults, motors starting, or electric heaters turning on, or they are caused by abrupt increases in source impedance, typically caused by a loose connection. They are the most common power disturbance. At a typical industrial site, it is not unusual to see several sags per year at the service entrance, and far more at equipment terminals.

Voltage dips can arrive from the utility; however, in most cases, the majority of sags are generated inside a building. For example, in residential wiring, the most common cause of voltage sags is the starting current drawn by refrigerator and air conditioning motors.

Dips do not generally disturb incandescent or fluorescent lighting, motors, or heaters. However, some electronic equipment lacks sufficient internal energy storage and, therefore, cannot ride through sags in the supply voltage. Equipment may be able to ride through very brief, deep sags, or it may be able to ride through longer but shallower sags.
2) **Very Short Interruption**

When the RMS value of voltage deviates for duration less than 1 minute, it is termed as long duration voltage variation. Each type of variation can be designated as instantaneous, momentary, or temporary, depending on its duration. It may be categorized as interruption. It occurs when the supply voltage or load current decreases to less than 0.1 PU for a period of time not exceeding 1 min.

3) **Long Interruption**

Total interruption of electrical supply for duration greater than 1 to 2 seconds.

It is always due to component outages. Component outages are due to three different causes:

1. A fault occurs in the power system which leads to an intervention by the power system protection. If the fault occurs in a part of the system which is not redundant or of which the redundant part is out of operation the intervention by the protection leads to an interruption for a number of customers or pieces of equipment. The fault is typically a short-circuit fault, but situations like overloading of transformers or under frequency may also lead to long interruptions. Although the results can be very disturbing to the affected customers, this is a correct intervention of the protection. Would the protection not intervene, the fault would most likely lead to an interruption for a much larger group of customers, as well as to serious damage to the electrical equipment.

As distribution systems are often operated radially (i.e., without redundancy) and transmission systems meshed (with redundancy), faults in transmission systems do not have much influence on the reliability of the supply, but faults in distribution systems do.

2. A protection relay intervenes incorrectly, thus causing a component outage, which might again lead to a long interruption. If the incorrect tripping (or mal trip) occurs in a part of the system without redundancy, it will always lead to an interruption. If it occurs in a part of the system with redundancy the situation is different. For a completely random mal trip, the chance that the redundant component is out of
operation is rather small. Random mal trips are thus not a serious reliability concern in redundant systems. However, mal trips are often not fully random, but more likely when the system is faulted. In that case there will be two trips by the protection: a correct intervention and an incorrect one. The mal trip trips the redundant component just at the moment that redundancy is needed. Fault-related mal trips are a serious concern in redundant systems.

3. Operator actions cause a component outage which can also lead to a long interruption. Some actions should be treated as a backup to the power system protection, either correct or incorrect. But an operator can also decide to switch off certain parts of the system for preventive maintenance. This is a very normal action and normally not of any concern to customers. There is in most cases at least some level of redundancy available so that the maintenance does not lead to an interruption for any of the customers. In some low voltage networks there is no redundancy present at all, which implies that preventive maintenance and repair or changes in the system can only be performed when the supply to a part of the customers is interrupted. These interruptions are called "scheduled interruptions" or "planned interruptions."

4) **Voltage Swell**

Voltage Swell is defined by IEEE 1159 as the increase in the RMS voltage level to 110% - 180% of nominal, at the power frequency for durations of ½ cycle to one (1) minute. It is classified as a short duration voltage variation phenomena, which is one of the general categories of power quality problems mentioned in the second post of the power quality basics series of this site. Voltage swell is basically the opposite of voltage sag or dip.

![Figure (3): Voltage Swell](image)
The disturbance is also described by IEEE C62.41-1991 as “A momentary increase in the power-frequency voltage delivered by the mains, outside of the normal tolerances, with a duration of more than one cycle and less than a few seconds”. However, this definition is not preferred by the power quality community.

Swells are subdivided into three categories:

<table>
<thead>
<tr>
<th>Voltage Swell</th>
<th>Magnitude</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instantaneous</td>
<td>1.1 to 1.8 pu</td>
<td>0.5 to 30 cycles</td>
</tr>
<tr>
<td>Momentary</td>
<td>1.1 to 1.4 pu</td>
<td>30 cycles to 3 sec</td>
</tr>
<tr>
<td>Temporary</td>
<td>1.1 to 1.2 pu</td>
<td>3 sec to 1 min</td>
</tr>
</tbody>
</table>

Table (1): Voltage Swell Categories

Voltage swells are characterized by their RMS magnitude and duration. The gravity of the PQ problem during a fault condition is a function of the system impedance (i.e. relation of the zero-sequence impedance to the positive-sequence impedance of the system), location of the fault and the circuit grounding configuration. As an example, on an ungrounded system, the line-to-ground voltages on the unfaulted phases can go as high as 1.73 pu during a SLG fault. On the contrary, on a grounded system close to the substation, there will be no voltage rise on the unfaulted phases because the substation transformer is usually connected delta-wye, providing a low impedance zero-sequence path for the fault current.

5) **Harmonic Distortion**

Voltage or current waveforms assume non-sinusoidal shape. The waveform corresponds to the sum of different sine-waves with different magnitude and phase, having frequencies that are multiples of power-system frequency.
THD:
Is defined as ratio of the power in the supply due to all the harmonics and the power of the fundamental supply.

![Figure (4): Power quality problems](image)

6) Voltage Unbalance

There are two commonly used definitions of Voltage Unbalance in the industry. These are:

1. NEMA Definition: NEMA stands for National Equipment Manufacturers Association in USA. NEMA definition of voltage unbalance is given by:

   \[
   \text{Voltage Unbalance} = \frac{\text{Maximum deviation from the mean of } V_{ab}, V_{bc}, V_{ca}}{\text{Mean of } V_{ab}, V_{ac}, V_{Ca}}
   \]

   NEMA definition is also called Line Voltage unbalance rate (LVUR) since Line voltages (i.e. Phase-Phase voltages) are only used for calculation. Line to neutral voltage should not
be used as zero sequence components can give incorrect results. Additionally, phase angles are not included in the equation. As can be observed, calculating the NEMA voltage unbalance is relatively straightforward.

2. True Definition: This definition of voltage unbalance is also known as ‘True definition’, ‘IEC Definition’ or ‘Voltage Unbalance factor’. Based on this, the percent voltage unbalance is defined as the ratio of negative sequence voltage (V2) to the positive sequence voltage (V1).

\[
\text{Voltage Unbalance} = \frac{V_2}{V_1}
\]

If you are wondering what negative and positive sequence voltages are, here is a simple explanation. Three phase voltages (or currents), balanced or unbalanced can be mathematically expressed as a sum of positive, negative and zero sequence components. It is a mathematical technique that is used extensively in power system engineering and its details can be found in many power engineering text books. For example, if we have an unbalanced voltage that is vectorially represented as shown below it can be separated into its constituent positive, negative and zero sequence components as shown. Out of these we will use the negative and positive sequence voltage magnitudes to calculate the unbalance. Note that positive sequence voltage creates flux in the direction that the motor is intended to rotate.

Negative sequence voltage rotates in the opposite direction (vectorially) from positive sequence and hence creates flux in the opposite direction. The positive sequence voltage will be much larger than the negative sequence and hence the direction of rotation of the motor is not
affected. However, the counter rotating negative sequence flux will create additional heating in the motor.

Why zero sequence voltage unbalance is not used? This is because, zero sequence currents cannot flow in induction motor loads that are most affected by voltage unbalance. Induction motor windings are almost always connected in delta or ungrounded wye. Hence calculating the zero-sequence voltage unbalance is not very useful practically.

Below is a calculator that can be used to calculate the voltage unbalance using the true definition or the IEC definition. The calculator calculates the positive, negative components of the system voltage and uses that to estimate the ‘true’ voltage unbalance.

There could be difference in the %unbalance calculated by both the methods which is perfectly normal. NEMA definition does not account for phase angles and hence this can be expected. Induction motor will always respond to the ‘true’ value of the voltage unbalance as this is the only equation that uses both positive and negative sequence voltages. Negative sequence is at the core of producing counter rotating magnetic flux inside the motor and the resulting heating.

### 1.2 Capacitor Bank:

Capacitor bank is used to improve the power factor in the electrical networks

#### 1.2.1 General Overview

Capacitor is a passive two terminal electrical component used to store energy electrostatically in an electric field. the forms of practical capacitors vary widely, but all contain at least two electrical conductors separated by a dielectric (insulator) shown in (Figure 5)
$C = \frac{\epsilon A}{d}$

Where ‘C’ is capacitance, ‘A’ is plate area, ‘d’ is the distance between two plates and ‘\(\epsilon\)’ is material permittivity.

As energy storage element, the capacitor has the following advantages:

1. Long life, with little degradation over 100 of thousands of cycles. Due to the capacitor's high number of charge-discharge cycles
2. Low cost per cycle
3. Good reversibility
4. Very high rates of charge and discharge
5. Extremely low internal resistance (ESR) and consequent high cycle efficiency (95% or more) and extremely low heating levels
6. High output power
7. Improved safety, no corrosive electrolyte and low toxicity of materials.
2.2 Power Factor Correction by using Capacitor Bank:

In three phase system, the power factor is improved by connecting the capacitors in star or delta. The star and delta connected banks are shown in the figure below.

![Figure (6): Delta and Star connected capacitor Banks](image)

Let, $V_L$ = Line voltage
$V_p$ = phase voltage
$C_\Delta$ = capacitor per phase when the capacitors are connected in delta

$C_y$ = capacitance per phase when the capacitor is connected in stars
$Q_c$ = VAR rating of each phase

**Delta Connection**

$V_p = V_L$ The capacitance per phase is given by the equation

$$C_\Delta = \frac{Q_c}{\omega V_p^2} = \frac{Q_c}{\omega V_L^2} \quad \text{equation (1)}$$

**Star Connection**
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The capacitance per phase is expressed by the equation

$$ V_P = \frac{1}{3} V_L $$

From equation (1) and (2) we get:

$$ C_Y = \frac{Q_c}{\omega V_P^2} = \frac{Q_c}{\omega \left(\frac{V_L}{\sqrt{3}}\right)^2} = \frac{3Q_c}{\omega V_L^2} \quad ... equ(2) $$

From equation (1) and (2) we get:

$$ C_Y = 3C_{\Delta} \quad ... equ(3) $$

The equation (3) shows that the capacitance requires in star connection of three phase transformer is equal to three times the capacitance requires per phase when the capacitors are connected in delta. Also, the working voltage of the star connected bank is \( \frac{1}{\sqrt{3}} \) equal to the delta connected bank.

For these reasons, the capacitors are connected in the delta in three phase systems for power factor improvement. Delta connection is also better if the capacitors are designed for higher working voltage.

**Disadvantages of low power factor:**

Power factor play an important role in AC circuits and power dissipation depends on this factor. For instant, we know that;

Power in a Three Phase AC Circuit,

$$ P = \sqrt{3} \ V \times I \cos\Phi $$

And Current in a Three Phase AC Circuits,

$$ I = \frac{p}{3 \ v \cos\Phi}, \ I \propto \frac{1}{\cos\Phi} \quad (1) $$

Also, Power in a Single Phase AC Circuits,

$$ P = V \times I \cos\Phi $$

And Current in a Three phase AC Circuits,

$$ I = \frac{p}{v \cos\Phi}, \ I \propto \frac{1}{\cos\Phi} \quad (2) $$
It is clear from both equations (1) and (2) that Current “I” is inversely proportional to CosΦ i.e. Power Factor.

Now, in case of Low Power Factor, Current will be increased, and this high current will cause to the following disadvantages.

1.) Large Line Losses (Copper Losses):
We know that Line Losses is directly proportional to the square of Current “I^2”
Power Loss = I^2xR
The larger the current, the greater the line losses i.e. I>>Line Losses In other words, Power Loss,

\[ I^2R = \frac{1}{\cos \phi^2} \]

Refer to Equation “

\[ I \propto \frac{1}{\cos \phi^2} \]  \hspace{1cm} (1) \]

Thus, if Power factor = 0.8, then losses on this power factor= \( \frac{1}{\cos \phi^2} = \frac{1}{0.8^2} = 1.56 \) times will be greater than losses on Unity power factor.

2.) Large kVA Rating and Size of Electrical Equipment:
As we know that almost all Electrical Machinery (Transformer, Alternator, Switchgears etc.) rated in kVA. But, it is clear from the following formula that Power factor is inversely proportional to the kVA i.e. CosΦ = \( \frac{kW}{kVA} \) Therefore, The Lower the Power factor, the larger the kVA rating of Machines.

3.) Greater Conductor Size and Cost:
In case of low power factor, current will be increased, thus, to transmit this high current, we need the larger size of conductor. Also, the cost of large size of conductor will be increased.
4.) Poor Voltage Regulation and Large Voltage Drop:

Voltage Drop,

\[ V = IZ. \]

Now in case of Low Power factor, Current will be increased. So, the Larger the current, the Larger the Voltage Drop.
And Voltage Regulation,

\[ V.R = (V_{\text{No Load}} - V_{\text{Full Load}}) / V_{\text{Full Load}} \]

In case of Low Power Factor (lagging Power factor) there would be large voltage drop which cause low voltage regulation.

5.) Low Efficiency:

In case of low Power Factor, there would be large voltage drop and large line losses and this will cause the system or equipments efficiency too low. For instant, due to low power factor, there would be large line losses; therefore, alternator needs high excitation, thus, generation efficiency would be low.

6.) Penalty from Electric Power Supply Company on Low Power factor:

Electrical Power Supply Company imposes a penalty of power factor below 0.95 lagging in Electric power bill. So, you must improve Pf above 0.95.
1.3 What’s next?

In chapter 2, We will discuss the components of switchboard, the types of it as function and protection and which role it takes in power flow. The definition of capacitor bank, its components and when it should work. The meaning of IP Code and shows the table of which material from capacitor we should use from its degree of protection against solid foreign objects and ingress of water indicated. The meaning of IP Form and shows the table of which assembly according to the degree of internal separation by barriers or partitions for different compartments. Definition of harmonics, what causes it, how to measure harmonic and how to reduce it.

In chapter 3, We will show the simulation of power factor correction by using Ecodial software and see what features and results we can get from it. Then we will take an example of a system under study “FOOD FACTORY” to show the difference between low loads and heavy loads on power factor and how to solve it using a capacitor bank.

In chapter 4, We will show the practical part in our project. The kit we use shows the low power factor at two conditions and how we to level it up again. The appearance of harmonics when start a non-linear load with a resonance from a coil. Then how the problem solved after using a capacitor bank or more than one, and by using an Anti-resonance.

In chapter 5, We will talk briefly about the whole topic in a summary.

Finally, The references for all we wrote.
CHAPTER 2

Power factor correction switchboard and harmonic problems

2.1 ELECTRICAL SWITCHBOARD

2.1.1 Introduction

An electrical device that directs electricity from one place to another is usually in the form of an electrical panel in an enclosure, which contains switches for such purposes. One of the more common configurations for an electric switchboard is a series of interconnected electrical panels. Each of the panels in turn features a series of switches that make it possible to control the flow of electricity. Making use of the switches, it is possible to adjust the voltage that is transmitted to connected devices, ensuring that the flow is not sufficient to cause damage to the circuitry. From this perspective, the electric switchboard can be viewed as a way of enhancing the safety of using electricity in the operation of various appliances, machinery, and other devices.

2.1.2 The Role of an Electric Switchboard in Power Flow

Electrical power systems work as power is sent from the supply which then in line moves through an electric switchboard. That switchboard then relays the electricity throughout a number of circuits. The power is then moved to feeders and then distributed to locations throughout the reach of the power grid.

An electric switchboard is an electrical device that distributes electricity from one electrical source to another electrical source. It is a major component used in Power distribution process. It is made up of several electric panels. Each electric panel contains switches that redirect electricity. An electrical switchboard is a single large panel or can be a combination of electrical panels on which switches and other power control equipment are fixed. The main purpose of the board is to control the flow of power. It divides the main current supplied to it into several smaller chunks and distributes it to the devices. In precise,
switchboards supply power to transformers, panels, and other equipment and from there power further gets distributed. An electrical switchboard gets power supply from a power generator or any other major power source. The operator working on controlling a board must be protected from electrocution. This is provided by fuses and switches mounted on the board. The amount of power received by switchboards must be equal to the amount of power distributed by them. There are controls which monitor this power distribution process. There are several load sharing controls, plus measurements devices mounted on the board to control power supply.

### 2.1.3 Types of Electric switchboards

There are several types of electric switchboards based on current rating, construction type, interrupt rating, operating type, voltage type, insulation medium, and others. Inner part of the board contains several bus bars, strips of aluminum and copper to which switches are connected. The main purpose of electric switchboards is to supply power to each and every single recipient electrical device. The amount of current should depend on the amount of power used by the device to function properly. The electrical board receives power from a major power source like generator and then gets distributed to each of the electrical devices or appliances used by the consumer.

### 2.1.4 Protection of Electric switchboards

Switchgear protection has been around for as long as we have had switchgears. The idea of the protection is that when we have an over current or overvoltage, a relay will notice it and react. The relay opens the breaker to avoid damage to the equipment. If the breaker is unable to break the circuit, then the feeders to that switchgear have to break the main breaker. That is how the infrastructure is established with switchgear protection. To get the relays to work properly different trip times for the relays were made. These have been calculated so that the correct relay trips at the right time.

### 2.2 Capacitor Bank switchboard

Capacitor bank is a grouping of several identical capacitors interconnected in parallel or in series with one another shown in the Figure

These groups of capacitors are typically used to correct or counteract undesirable characteristics, such as power factor lag or phase shifts inherent in alternating current (AC)
electrical power supplies. Capacitor banks may also be used in direct current (DC) power supplies to increase stored energy and improve the ripple current capacity of the power supply.

![Figure (7): Capacitor Switchboard](image)

### 2.2.1 Capacitor Switchgear

The capacitor switchgear has a following component:

1. **Capacitor:**
   
   Capacitors units connected in parallel. Each capacitor is placed in an enclosure and equipped with bushings.
(2) **Contactors:**

Contactor is an electrically controlled switch shown in the Figure, used for switching a power circuit, similar to a relay except with higher current ratings. A contactor is controlled by a circuit which has a much lower power level than the switched circuit.

* When current passes through the electromagnet, a magnetic field is produced, which attracts the moving core of the contactor. The Electromagnet coil draws more current initially, until its inductance increases when the metal core enters the coil. The moving contact is propelled by the moving core; the force Developed by the electromagnet holds the moving and fixed contacts together. When the contactor coil is de-energized, gravity or a spring returns the electromagnet core to its initial position and opens the contacts.
(3) **PF controller:**

It is a device used to automatically connect the capacitor and break it depend on the rate of change in reactive power in network, comparing the existing power factor by the target power factor which set by the user.
(4) **Reactor (detuned coil):**

To improve the power factor in a circuit that contains harmonics we will face some problems, and to solve this problem we need to connect a coil in series with the capacitor this coil is called Detuned coil.

Harmonics are unwanted electrical components that are most often spoken about in power quality parameters and cause problems when they exist over the limits set by the standards in the electrical system where harmonics are present, harmonic filter reactors are connected in series to the capacitors. The main purpose is to prevent the harmonic current flowing on the capacitor and to prevent the resonance of the system.

![Detuned Coil](image.png)

**Figure (11): Detuned Coil**

The detuned reactors (DR) are designed to protect the capacitors by preventing amplification of the harmonics present on the network. They must be connected in series with the capacitors.
(5) **Circuit Breaker**

Is a manually or automatically operated electrical switch designed to protect an electrical circuit from damage caused by overload or short circuit its basic function is to detect a fault condition and interrupt current flow. Unlike a fuse, which operates once and then must be replaced, a circuit breaker can be reset (either manually or automatically) to resume normal operation. Circuit breakers are made in different sizes, from small devices that protect an individual household appliance up to large switchgear designed to protect high voltage circuits feeding an entire city.
In the figure many symbols of circuit breaker:
2.3 IP-CODE

2.3.1 Definition

A two-digit number established by the International Electro Technical Commission, is used to provide an Ingress Protection rating to a piece of electronic equipment or to an enclosure for electronic equipment. The protection class after EN60529 are indicated by short symbols that consist of the two code letters IP and a code numeral for the amount of the protection. Example: IP65

The two digits represent different forms of environmental influence:

- The first digit represents protection against ingress of solid objects.
- The second digit represents protection against ingress of liquids
- The larger the value of each digit, the greater the protection. As an example, a product rated IP54 would be better protected against environmental factors than another similar product rated as IP42.
2.3.2 Degrees of protection against solid foreign objects indicated by the first characteristic numeral:

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Protected against solid foreign objects</td>
<td>Ø50 mm</td>
</tr>
<tr>
<td></td>
<td>larger than 50 mm</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Protected against solid foreign objects</td>
<td>Ø12.5 mm</td>
</tr>
<tr>
<td></td>
<td>larger than 12.5 mm</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Protected against solid foreign objects</td>
<td>Ø2.5 mm</td>
</tr>
<tr>
<td></td>
<td>larger than 2.5 mm</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Protected against solid foreign objects</td>
<td>Ø1 mm</td>
</tr>
<tr>
<td></td>
<td>larger than 1 mm</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Protected against dust (dust protected)</td>
<td>Ø</td>
</tr>
<tr>
<td>6</td>
<td>Dust tight</td>
<td></td>
</tr>
</tbody>
</table>

Table (2): IP code
2.3.3 Degrees of protection against ingress of water indicated by the second characteristic numeral:

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Protected against vertically falling water drops (condensation)</td>
</tr>
<tr>
<td>2</td>
<td>Protected against vertically falling water drops when enclosure tilted up to 15°</td>
</tr>
<tr>
<td>3</td>
<td>Protected against spraying water up to 60° from vertical</td>
</tr>
<tr>
<td>4</td>
<td>Protected against splashing water from all directions</td>
</tr>
<tr>
<td>5</td>
<td>Protected against water jets from all directions</td>
</tr>
<tr>
<td>6</td>
<td>Protected against powerful water jets from all directions</td>
</tr>
<tr>
<td>7</td>
<td>Protected against the effects of temporary immersion in water</td>
</tr>
<tr>
<td>8</td>
<td>Protected against the effects of continuous immersion in water</td>
</tr>
</tbody>
</table>

Table (3): IP code
2.3.4 Design and construction

Internal separation of assemblies by barriers or partitions (forms):

IEC60439-1 defines four basic “forms” of assembly according to the Degree of internal separation by barriers or partitions for different Compartments.

The defined forms are:

Form 1
Form 2: Form 2a & 2b
Form 3: Form 3a & 3b
Form 4: Form 4a & 4b

Each Form relates to the internal separation of the bus bars, functional units and terminals, each being defined as:

- **Bus bar** - low impedance conductor to which several electric circuits can be connected
  - Main bus bar - bus bar to which one or more distribution bus bar, incoming unit or outgoing unit can be connected
  - Distribution bus bar - bus bar in one section which is connected to the main bus bar from which incoming or outgoing units can be connected
- **Functional Unit** - part of the assembly comprising the electrical and mechanical elements that contribute to the fulfilment of the same function
  - Incoming unit - functional unit which feeds energy into the assembly
  - Outgoing unit - functional unit supplying energy to the outgoing circuits
- **Terminals** - part of the assembly which provide for connection of incoming and outgoing cable and bus bar
Figure (14): Panel Forms
### 2.3.5 Forms description:

<table>
<thead>
<tr>
<th>Main criteria</th>
<th>Subcriteria</th>
<th>Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>No internal separation</td>
<td></td>
<td>Form 1</td>
</tr>
<tr>
<td>Separation of busbars from the functional units</td>
<td>Terminals for external conductors not separated from busbars</td>
<td>Form 2a</td>
</tr>
<tr>
<td>Separation of busbars from the functional units</td>
<td>Terminals for external conductors separated from busbars</td>
<td>Form 2b</td>
</tr>
<tr>
<td>Separation of busbars from the functional units and separation of all</td>
<td>Terminals for external conductors not separated from busbars</td>
<td>Form 3a</td>
</tr>
<tr>
<td>functional units from one another. Separation of terminals for</td>
<td>Terminals for external conductors separated from busbars</td>
<td>Form 3b</td>
</tr>
<tr>
<td>external conductors from the functional units, but not from those of other</td>
<td></td>
<td></td>
</tr>
<tr>
<td>functional units</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Separation of busbars from all functional units and separation of all</td>
<td>Terminals for external conductors in the same compartment as the</td>
<td>Form 4a</td>
</tr>
<tr>
<td>functional units from one another. Separation of terminals for</td>
<td>associated functional unit</td>
<td></td>
</tr>
<tr>
<td>external conductors associated with a functional unit from those of any</td>
<td>Terminals for external conductors not in the same compartment as the</td>
<td>Form 4b</td>
</tr>
<tr>
<td>other functional unit and the busbars</td>
<td>associated functional unit, but in individual, separate, enclosed</td>
<td></td>
</tr>
<tr>
<td></td>
<td>protected spaces or compartments</td>
<td></td>
</tr>
</tbody>
</table>

Table (4): Forms Description
2.3.6 **Internal separation of assemblies by barriers or partitions (forms):**

As a conclusion, depending on rank of the form, the separations provide:
- Protection against contact with live parts of adjacent functional units.
- Protection against the passage of foreign solid bodies from other unit
- Limitation of the probability of initiating arcing faults.
- Limitation of transferring / propagation of an initiated arc from one Compartment to another / from one functional unit to another.

Hence, the forms have great impact on (Reliability, Availability, Maintainability and Safety).
2.4 Harmonics

2.4.1 Definition:
Harmonics are electric voltages and currents on an electric power system that can cause power quality problems. Because equipment and machinery can malfunction or fail in the presence of high harmonic voltage and/or current levels, harmonic distortion has become a growing concern for facility managers, users of automation equipment, and engineers. While the presence of harmonics won't make it impossible for a factory or office to operate, the degree of impact depends on how much the power system can withstand and how susceptible the equipment is to harmonic distortion.

2.4.2 What Causes Harmonics?
Harmonics are created by electronic equipment with nonlinear loads drawing in current in abrupt short pulses. The short pulses cause distorted current waveforms, which in turn because harmonic currents to flow back into other parts of the power system. Harmonics are especially prevalent when there are many personal computers, laser printers, fax machines, copiers, or medical test equipment, fluorescent lighting, uninterruptible power supplies (UPSs), and variable speed drives all on the same electrical system.

Harmonics degrade the level of power quality and its efficiency, particularly in a commercial building or industrial facility. In general, most buildings can withstand nonlinear loads of up to 15% of the total electrical system capacity without concern. If the nonlinear loads exceed 15%, some non-apparent negative consequences can result.

2.4.3 Common Problems Caused by Harmonics:
Harmonics caused by equipment such as VSDs can cause disturbances in the electrical grid that will not only affect equipment in the same installation, but also other consumers fed from the same transformer. Adverse effects of harmonics including additional heating and efficiency losses in transformers, motors and cables; random circuit breaker tripping; and interference with and damage to capacitor banks.
And here is some of harmonics main problems:

1) **Overloading Neutral Conductors**
   The three-phase system consists of three individual phase conductors and a neutral conductor. If all the phase conductors carry the same current, the phase currents tend to cancel one another out provided there is a balanced load. This balanced load makes it possible to reduce the size of the neutral conductor. Unfortunately, switched mode power supplies used in computers have a very high third-harmonic current. While harmonic currents cancel out on the neutral wire, the third harmonic current is additive in the neutral. In buildings with a large number of installed personal computers, the neutral wire can carry much higher currents than the wire was designed to accommodate, creating a potential fire hazard.

2) **Overheating Transformers and Increased Associated Losses**
   For transformers feeding harmonic-producing loads, the eddy current loss in the windings is the most dominant loss component in the transformer. This eddy current loss increases proportionate to the square of the product's harmonic current and its corresponding frequency. The total transformer loss to a fully loaded transformer supplying to a nonlinear load is twice as high as for an equivalent linear load. This causes excessive transformer heating and degrades the insulation materials in the transformer, which eventually leads to transformer failure.

3) **Nuisance Tripping of Circuit Breakers**
   All circuits containing capacitance and inductance have one or more resonant frequencies. When any of the resonant frequencies correspond to the harmonic frequency produced by nonlinear loads, harmonic resonance can occur. Voltage and current during resonant frequency can be highly distorted. This distortion can cause nuisance tripping in an electrical power system, which can ultimately result in production losses.
2.4.4 Total Harmonics distortion:

The total harmonic distortion (THD) is a measurement of the harmonic distortion present in a signal and is defined as the ratio of the sum of the powers of all harmonic components to the power of the fundamental frequency.

For example, in audio systems, lower distortion means the components in a loudspeaker, amplifier or microphone or other equipment produce a more accurate reproduction of an audio recording.

In radio communications, lower THD means pure signal emission without causing interferences to other electronic devices.

In power systems, lower THD means reduction in peak currents, heating, emissions, and core loss in motors.
2.4.5 Power Analyzer:
Other method to measure the harmonics is Power Analyzer

\[
V_{THD_F} = \frac{100 \sqrt{V_{RMS}^2 - V_{1_rms}^2}}{V_{1_rms}}
\]

\[
I_{THD_F} = \frac{100 \sqrt{I_{RMS}^2 - I_{1_rms}^2}}{I_{1_rms}}
\]

\[
V_{THD_R} = \frac{100 \sqrt{V_{RMS}^2 - V_{1_rms}^2}}{V_{RMS}}
\]

\[
I_{THD_R} = \frac{100 \sqrt{I_{RMS}^2 - I_{1_rms}^2}}{I_{RMS}}
\]

Figure (16): THD

Figure (17): Power Analyzer
Power quality analyzer measure the power in W, kWh or to analyze and measure harmonics. This power analyzer is a multi-function power analyzer device that measure precisely direct current, alternating current, AC-voltage, DC-voltage the intensity of DC or AC, phase rotation and idle, apparent and effective power. The reading of AC power is considered the real value and has a maximum range of 6000 Watts. While a reading is being taken, the polarity changes automatically, if negative values are taken then a minus sign will appear on the device display.

2.4.6 Harmonic filtering

There are main types of harmonic filters used:
- passive filter
- active filter
- hybrid filter (active and passive together)

a. Passive Harmonics Filter:

Passive harmonics filters are the more common filters used in to get rid of harmonics. These filters utilize components like inductors and capacitors. Passive filters generally filter noise on a single variable speed drive. They eliminate harmonics before the electrical current reaches equipment.

Passive filters are more simple and low costed than active filters.
b. **Active harmonic filter:**

Active harmonic filters are parallel filters (which means the current doesn’t go through the filter) that are used to reduce, or mitigate, harmonics to tolerable levels as defined by IEEE-519. Active filters use a set of transistors and capacitors to filter (or clean) the current wave by injecting inverse currents to cancel out the undesired harmonic components. Active filters are significantly more expensive than passive filters and take up more space. Size is an immense factor in system design today and should be accounted for when deciding on what type of harmonic filter is right for you.

Active filters can work with multiple drives; when the active filter reaches its limit, it won’t overload. In addition, if an active filter breaks, it won’t stop the motor (since current isn’t going through the filter); it just won’t filter the current wave.
c. **Hybrid harmonic filter:**

Combination between both filters active filter and passive filter, each one has its own work, as the passive filter set to eliminate the higher harmonic order which help in decreasing the coast of the active filter, also the capacitor in the passive filter make an automatically correction to the power factor, active filter reduce, or mitigate the rest harmonics orders.
d. **Harmonic Filter (Detuned) Reactor:**

To improve the power factor in a circuit that contains harmonics we will face some problems, and to solve this problem we need to connect a coil in series with the capacitor, this coil is called Detuned coil.

Harmonics are unwanted electrical components that are most often spoken about in power quality parameters and cause problems when they exist over the limits set by the standards in the electrical system where harmonics are present, harmonic filter reactors are connected in series to the capacitors. The main purpose is to prevent the harmonic current flowing on the capacitor and to prevent the resonance of the system.

**What is Harmonic Filter (Detuned) Reactor?**

The harmonic filter (Detuned) reactor is a fixed impedance load in the structure of the coil calculated according to certain calculations.

**Why Harmonic Filter (Detuned) Reactor is used?**

The harmonic filter (Detuned) is to limit the flow of harmonic current from non-linear loads on the reactor to the fixed impedance loads (e.g., capacitor).
If we look to the impedance equation of the capacitor, it is seen that the capacitor impedance decreases with the increase of the frequency. In this case, the current will flow at low impedance so that the total current on the capacitor will be equal to the sum of the nominal coupling current and the harmonic current. An unwanted state will occur on the capacitor due to the harmonic current.

Total Current = Nominal coupling current + Harmonic coupling current

To reduce the harmonic coupling current we need to increase the line impedance to which the capacitor is connected. As can be seen in Formula 2, the high impedance bobbin at high frequencies is possible by connecting the capacitor in series.

\[ X_L = 2\pi x F x L \]

Formula 2 - Calculation of Coil Impedance

\[ X_T = X_C + X_L \]

Formula 3 - Calculation of Total Equivalent Impedance

At this point the total impedance will be equal to the sum of the capacitor and coil impedance and the harmonic current flowing on this arm will be reduced to the lowest level.

Harmonic Filter (Detuned) Reactors can be manufactured as single-phase or three-phase, choosing the tuning frequency according to the dominant harmonic current order in the system according to the bus bar voltage and capacitor impedance / power.

Harmonic filter (detuned) reactors do not destroy harmonic components in the system. It only prevents the harmonic current from increasing in amplitude. It is a well-known misinformation to say that it destroys harmonics in the system.

IV. What are the advantages of using Harmonic Filter (Detuned) Reactor?
- Prevents harmonic current and voltage amplitude from increasing in systems with non-linear loads.
- Limits the harmonic current flowing on the capacitor. This prevents heat and high current stresses and allows the capacitors to have a longer operating life.
- Prevents overcurrent and heating problems on transformers, bus bars, cables, switchgear, protection equipment, etc…
CHAPTER 3

Simulation of Power Factor Correction

3.1 Introduction:
Ecodial is low voltage electrical installation design software developed by Schneider Electric. It actually calculates LV electrical networks and helps you to choose the right equipment and to optimize your electrical installation. Generally, there are typical analysis that are applied to distribution networks such that load flow and short circuit studies. These studies enable the designer to have a proper design of the network components. The distribution network components that should be chosen carefully are,

- Supply transformers,
- Distribution switchgear components like busbar – circuit breakers – load break switches – fuses – contactors – overload relays. All these components should have a suitable setting that suitable with the nature of loads, and
- Cables

LV Distribution Network is the final stage in the delivery of electricity to end users, LV networks are the most part of the electrical power system that are subjected to repetitive faults due to human and non-skilled persons that are considered end users.

3.2 ECODIAL Software

3.2.1 The Ecodial software has the following features.
- It is used for LN distribution only (up to 1000v),
- It is used to simulate different levels in the LV distribution (main – sub - final),
- It used for LV high frequency applications like aircraft (400Hz applications),
- It may apply different type of earthing systems (IT – TT - TN),
- it is used to simulate different types of LV common loads such as lighting, outlet sockets, motors, and static loads.
- It implements the capacitor banks for power factor correction to get the targeted power factor and prevent any penalty factor on the customers.

- It allows the coordination between the MCC components.

If you need a snapshot calculation Ecodial provides you with reliable results in a few clicks. If you need to easily find a product without entering into the Schneider Electric catalogue, Ecodial offers you a technically-oriented search engine for selection of a product, discrimination and cascading.

### 3.2.2 What can we do with ecodial?

- You select quickly and easily an LV network made with a single branch at three levels.
- You customise the few input parameters to meet your requirements.
- You let the power engine calculate for you in compliance with electrical standards.
- You visualise the discrimination limits of your protective device system by using versatile tripping-curve diagrams.
- You print out a comprehensive and clear report to prove your calculation

### 3.2.3 Switchgear status and operating modes

This property determines the \textit{open/closed (off/on)} position of circuit breakers and switches in the various operating modes. Ecodial can manage different status conditions of switchgear depending on the operating mode.

This makes it possible to take into account installations supplied by multiple sources, those offering load shedding and those with seasonal operating modes, for example.

When the status of a circuit breaker or switch is “\textit{closed}“, the circuit downstream of the circuit breaker (or switch) is supplied in the current operating mode. When the status of a circuit breaker or switch is “\textit{open}“, the downstream circuit is not supplied in the current operating mode.
When a part of the network is not supplied in a given operating mode, it is shown in blue in the single-line diagram. Given that the “closed” status condition is the most common in installations, only the “open” status condition is shown in the single-line diagram.

3.3 ECODIAL Projects: (Food Factory)

- The loads data entry is the first step to design the network of any projects. Food factory is designed in three stages, the project is proposed by Ecodial and the following results are obtained,
- Front page.
- Power summation is performed to calculate the loads currents.
- Complete calculation is obtained for each circuit in the project.
- Discrimination study is obtained for the network.
- Single line diagram of the network.
- Components list with the proper setting.
3.3.1 First factory

We started the simulation process with selecting the power factor to not be less than 0.9 to avoid the penalty.

After adding the first factory and start calculating the results we found that there's no error detected with the load applied.
3.3.2 Second Factory

Figure (23): Adding new branch to first factory

Then after extending with the second branch and calculating the result, it detected an error cause of the power factor is less than the target power factor.

Figure (24): Error existence due to low power factor
Figure (25): Results after adding capacitor bank

Then after adding the capacitor and calculating the result, it seems that the error is removed. And it seems that there is more apparent power to add a new branch with more loads.
3.3.3 Third Factory

Figure (26): Results after adding new branch

Then after adding the third branch, it worked without any error after added the capacitor in previous step as shown.
Chapter 4

Experimental Results of Power Factor Correction

4.1 General Overview

4.1.1 Components

We made a practical experiment on this kit which consist of:

- Lamps
- Contactors
- Controller
- Circuit breakers
- Coils
- Capacitors

Figure (27): Practical Kit
We study three different cases; the first case describes the linear loads cases and the effect of capacitor on improving the power factor, the second case focus on power quality problems as we add a harmonic generator and test the harmonics before and after adding the capacitor bank, third case describe the resonance case and how we can solve this problem.

Figure (28): Kit Diagram
4.2 Experimental Results

4.2.1 At Case 1:

The lamp 1,2 switched on and acting as a linear load on the system

![Image of linear load case]

Figure (29): Linear Load Case

When the lamp 1,2 switching on, the power factor is decreased and the controller automatically contact the first capacitor to improve the power factor as shown in the following figures.
(1) Before adding capacitor:

Figure (30): Power Factor measurements before adding Capacitor

(2) After adding capacitor:

Figure (31): Power Factor measurements after adding Capacitor
And by observation the harmonics the result was expected that the harmonics was almost nonexistent because linear load not generate harmonics.

4.2.2. **At Case 2:**

For testing the Power Quality and the effect of adding capacitor bank to network that contains harmonics, we must add any harmonics generator either by nonlinear load or make a saturation in the coil.

By switching two more lamps in parallel with lamps 1,2 the equivalent resistance become very small and the volt will increase in the coil which is connected series with the parallel lamps which leads to saturation in the coil and harmonics is generated.

![Harmonic Spectrum at Linear Loads](image-url)
By adding the two lamps 3,4 the controller automatically will add the second capacitor to improve the power factor.

(1) Before adding capacitor:

Figure (33): Saturation in Coil to generate Harmonics

Figure (34): Power Factor measurements before adding Capacitor
(2) After adding capacitor:

![Image of power factor meter](image)

**Figure (35): Power Factor measurements after adding Capacitor**

By observation the harmonics it notes that the harmonics increase after the saturation occurs in the coil and by adding the capacitor bank it was expected the harmonics will increase.
(3) Before adding capacitor:

![Figure (36): Harmonics Spectrum with existence of Harmonic generator](image1)

(4) After adding a capacitor:

![Figure (37): Harmonics Spectrum with existence of Harmonic Generator & Capacitor](image2)
4.2.3. **At Case 3:**

To study the resonance case, we switched on a coil that has reactance \( X_L \) equal to the reactance of the capacitor \( X_C \) so parallel resonance is occurred between them that cause:

1- Noise
2- Increasing harmonics as showing in the figure (34)

![Figure (38): Harmonic Spectrum when Resonance case occurs](image)

The solution for the resonance problems is adding a series coil with the capacitor (detuned coil) which help in:

1- Increasing the reactance of the capacitor line so it detuned the harmonics attack from the line.
2- Shifting the resonance to another frequency which is not existing in the network.
As shown, when Detuned coil is series with capacitor bank it leads to improving low power factor without making more Power Quality problems.
CHAPTER 5

Conclusion

This graduation research is concerned with the power factor correction panels in the level of Low Voltage distribution networks. It is considered with the effect of the power factor correction on the network performance and power quality.

In addition to the standard construction components of the LV switchboard, the power factor correction switchboard has the following main components,
- Capacitor units,
- Capacitor contactor,
- Reactive power controller, and
- Detuned coil.

The nonlinear loads are considered harmonic generators, it injects harmonic to the network. This harmonics take the capacitor circuit to attack due to reduction in the capacitive reactance with high frequency.

According to the weighted value of the nonlinear loads in the low voltage distribution network, the capacitor bank type should be carefully chosen, these types are:
- Standard type: it is rated to the rated voltage of the network,
- Overrated type: it is rated to 10% above the rated voltage, and
- Overrated plus detuned coil: it can prevent the harmonic attack inside the overrated capacitor.

If the nonlinear loads have been increased to certain level, the filtering solution should be implemented (either active or passive filter).

In this research, manual calculations are performed to,
- Study the effects of power factor improvement on simple distribution network.
- Analyze the total harmonic distortion in voltage due to nonlinear loads.
Ecodial Software is implemented to simulate the effect of power factor correction on the power flow on a certain application of LV distribution networks. It has been proven that implementing capacitors to improve the power factor leads to:
- The voltage drop will be reduced,
- The line losses will be reduced, 
- The reserve power from the supply transformer will be increased, and 
- The rating of the network components will be reduced.

A practical kit which presents Power Factor Correction by using Capacitor bank in linear loads and non-linear loads without affecting the Power Quality problems.
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<td>Figure 25</td>
<td>Result after adding capacitor bank</td>
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<td>Figure 26</td>
<td>Result after adding third branch</td>
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<td>Figure 31</td>
<td>Power factor measurements after adding capacitor</td>
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<td>Harmonic spectrum at linear loads</td>
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<tr>
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</tr>
<tr>
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<td>---------</td>
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<tr>
<td>P</td>
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</tr>
<tr>
<td>Q</td>
<td>Reactive power</td>
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<td>S</td>
<td>Apparent power</td>
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<td>Φ</td>
<td>Power factor angle</td>
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<td>C</td>
<td>Capacitance</td>
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<td>V</td>
<td>Voltage</td>
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