

How to get the most from Automatic Power Factor Compensation

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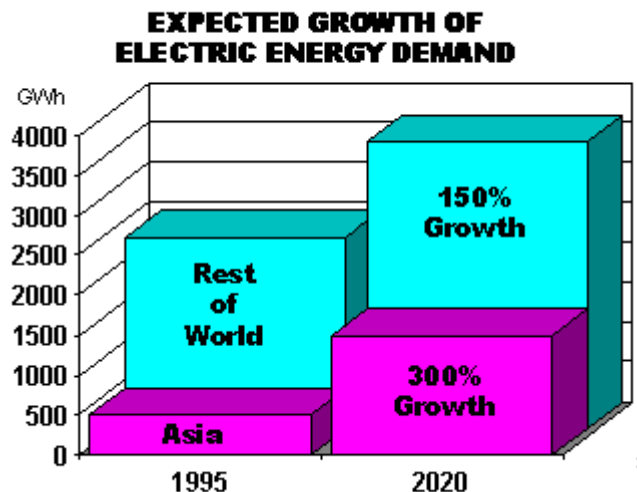
ABSTRACT

Increasingly, Indian Industry is paying one of the highest power tariffs in the world. Countries in this club such as Germany and Italy have benefited from Automatic Power Factor control as a competitive edge. They are already global leaders in Automatic Power Factor Compensation (APFC) Capacitors and Panels. This paper is aimed at APFC users and takes a hands-on look at **extending the lifetime payback** of APFC equipment. The effects of Current, Voltage, Harmonics and Temperature and their interplay are discussed. These produce degradations in Capacitors and Contactors. Subtle problems go unnoticed since the equipment is operating silently in a corner, until a catastrophic breakdown occurs. This paper also discusses practical guidelines for panel designers and users. Peak Inrush Current limiting, forced cooling, Component specifications, component selection and the role of the APFC controller with its protective functions are examined.

1 Energy Efficiency, the Competitive Edge

The demand for energy is projected to grow twice as fast in Asia as for the rest of the world over the next 20 years. India is projected to claim a significant portion of this Asian demand.

However, with a smaller reserve of resources, Electricity prices in Asian countries are already some of the highest in the world. The per-unit cost in India is almost twice that in Canada. With increasing global competition, countries with higher electricity costs can benefit significantly from improvements in Energy Efficiency. Further, improvements in energy efficiency are already proven to have the fastest payback, compared to improving availability through Generation.



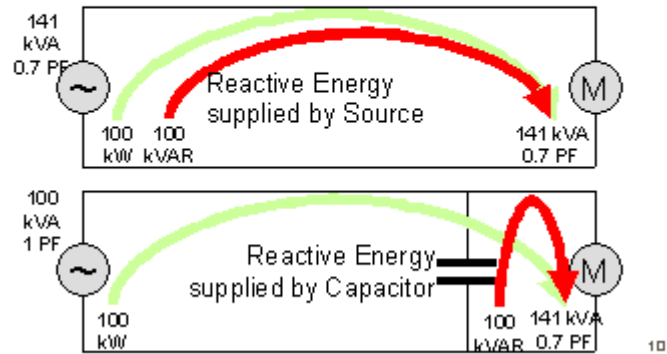
Power Factor (PF) improvement is therefore one of the fastest ways to a better bottom-line.

2 The Principle of PF Compensation

While the ideal Power Factor (PF) is Unity or 1, most Industrial loads have a PF lower than 1. Moreover, this lower PF is usually Inductive, arising out of the windings of Transformers, Motors, and the like. These loads consume kVARs (the Wattless component) from the supply line.

PRINCIPLE of PF Compensation

Eg. Motor Load needs 100kVAR of Reactive Energy



The principle of PF Compensation is to supply these kVARs via a capacitor located close to the load, reducing the current drawn from the supply line.

3 Automatic PF Compensation

For an Industry with dynamically changing loads, Automatic PF Compensation affords the best Return on Investment, since the kVAR investment required is smaller than with fixed capacitors needed to meet the entire load.

Automatic PF Correction also avoids Leading PF situations by switching off extra capacitors.

4 Who can benefit from Automatic PF Compensation (APFC)?

- Industries
- Commercial Complexes
- Housing Complexes
- Hotels
- Software Development Centers
- Services like Airports, Dockyards

5 Who supplies APFC Equipment?

- Capacitor Manufacturers
- Panel Builders
- Specialized Manufacturers
- Integrators
- Energy Services Companies (ESCOs)

6 Important Issues for APFC Panel Manufacturers

7 Components of APFC Panels

- Lowest Cost of:
 - Manufacturing. Usually this is top of mind
 - **Life-time.** This aspect is rarely targeted and includes site visits, trouble-shooting, replacements, repairs, etc.
- Flexibility in Design
 - Reduced Inventory
 - Last Minute Tuning
- Fast Delivery
- Equipment Reliability
- Lowest Field Problems

The 5 C's which comprise APFC panels are:

- Capacitors
- Contactors
- Controller
- Cabinet
- Cabling and safety parts (fuses, etc)

The important considerations are:

- Relatively Low-Tech Product, so competition and pressure on initial cost
- Each part influences other parts
- Redundancy is rarely possible

8 Capacitor Construction, Factors affecting Life-Time cost

The PF Capacitor can be visualised as a pair of conductive surfaces (the plates) separated by an insulating dielectric. One layer of this sandwich is barely 10 to 20 micron thick.

8.1 The Dielectric

Older capacitors were made with a paper dielectric immersed in a heavy mineral oil called PCB (poly-chlorinated-bi-phenyl). These were bulky and ran very hot even though the oil aided heat dissipation. But they were robust, since the high Tan Delta (resistive) loss of the PCB oil dielectric provided built-in inrush protection. Also, PCB is so stable that it never degraded, even in discarded capacitors in waste dumps, contaminating ground water and the environment. Unfortunately, PCB is carcinogenic. Finally, it was banned.

Today, the dielectric is usually a 6 micron-thick PP (polypropylene) plastic film, free from impurities or pin holes. PP has excellent physical (non-tearing) and electrical (very low loss) properties for a dielectric. Especially its self-healing property, which is explained shortly. Unfortunately, the low loss allows high inrush current. To make things worse, fuses for the capacitors are either excessively sized or are missing altogether. In addition, PP a petroleum derivative is extremely flammable. An inadequately designed APFC panel causes capacitor overheating, which is as dangerous as smoking over a drum of petrol.

Some better capacitors have a combination paper-film dielectric 15 micron thick. This can result in a higher purchase cost, but a lower lifetime cost since it is far more reliable and requires fewer replacements.

8.2 The Conductive Surface

The conductor surface may be merely a thin metal spray on the plastic dielectric film. This

gives a low-cost but weak construction. Capacitors that are more reliable may use aluminum foil, or thicker vapor-deposited aluminum, on both sides of the dielectric film.

Thicker dielectrics and foils are more reliable (better inrush current and voltage surge withstanding), but also require more surface area for a given capacitance. This means more material, larger capacitor cans and slightly larger panels.

8.3 75% of the APFC Investment

The Capacitor is placed in series with a switch, a heavy-duty relay, called a Contactor. These two components comprise 75% of the cost of an APFC panel. The contactor must be rated for Capacitor switching duty, specified for inrush current typically 100 In

The APFC Panel designer and user must therefore consider a judicious specification, since the lowest bid does not usually give the lowest lifetime cost.

9 APFC Panel Design Considerations: Critical Factors

The APFC Panel designer attempts to simultaneously minimise:

- Field trouble and
- Cost

In other words, how to achieve a given lifetime cost (which the Manufacturer would like to minimise) whilst meeting the specifications (which the User would like to maximise) and the attendant field conditions.

Most Application related problems arise from:

- Improper Design or Component Sizing, or
- Improper Installation, Settings or Use

This results in:

- Damage or Reduced ability to Compensate
- Higher Maintenance
- PF and kVA Demand Penalties to the User. The latter is because poorer PF immediately raises the kVA consumed by a given reactive load.

The key operating conditions to be considered are the peaks of

- **Current. Especially due to Inrush and Harmonic Current and**
- **Voltage**

- **Temperature.**

These determine the life of Capacitors and Contactors, which comprise almost 75% of the cost of an APFC Panel.

Unfortunately, these conditions are not often precisely known at the time of designing the Panel. Nor would they stay constant thereafter, since newer (e.g. non-linear) loads may be added at site from time to time. Later, this paper shows how the APF Controller provides some protection from these detrimental effects.

10 APFC Economics

The cost breakup of a typical APFC Panel for LT 415v application, is:

- Capacitors 50%
- Contactors 25%
- Cabinet 15%
- Cabling, Safety Parts 5%
- Controller 5%

Contracting adds a 20% overhead. These are only typical figures, and may vary.

The astute reader would notice:

- **The Controller is the Brain of the system**
- **The Controller must provide the intelligence to protect the equipment. I.e., brain rather than brawn. Safety alarms and tripping, a critical necessity, is enabled by the fact that it is the Average PF for the month that needs to be maintained. Instantaneous PF need not be maintained during abnormalities.**
- **This is the ONLY way to minimize the cost of the complete panel. Without well-designed protection facilities in the Controller the alternative, of over-sizing or over-rating the components to meet the exigencies at site, is far more costly.**

11 APFC Panel Design Critical Factors: Capacitors

11.1 Current

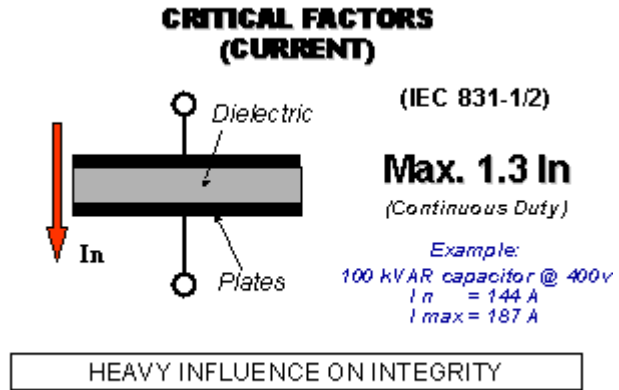
IEC831-1 and IEC831-2 specify an I_{max} of 1.3 times I_n , the nominal current, for continuous duty. Higher current are detrimental to both the Capacitor and the Contactor, particularly from repetitive conditions like:

- Harmonics
- Inrush
- Line over-voltage

Some of the a-periodic events that degrade the life of capacitors and contactors are

- Micro interruptions
- Mains outages, especially supply restoration
- Contactors chatter / failure and
- Resonance

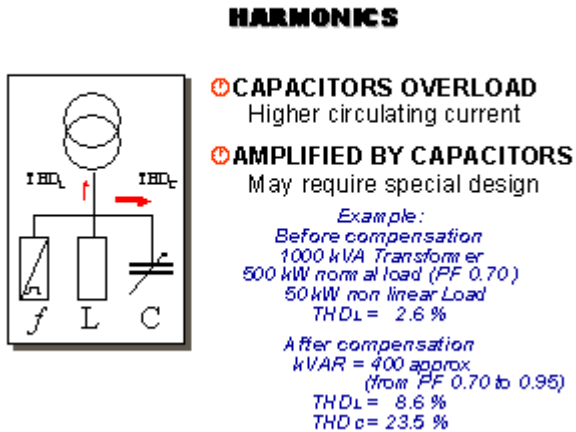
These conditions, though triggered by Voltage, also result in large current surges through the capacitors.



The APFC controller can extend capacitor and contactor life considerably by bringing in protective functions during these harmful conditions.

We now examine these detrimental conditions.

11.1.1 Harmonics

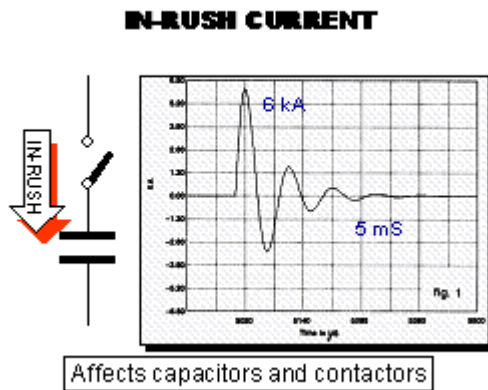


Capacitors present lower impedance to higher frequencies. Capacitors thus tend to amplify harmonic current drawn and/or supplied via a distorted voltage supply waveform. Sometimes this calls for special design such as oversized components. Harmonics cause capacitor overload and over-heating through higher circulating currents.

Examples of loads that can distort the supply voltage:

- Switching Power supplies (e.g. UPS, software companies),
- Rectifier converters (e.g. Chlor alkali industry),
- Variable speed variable frequency drives

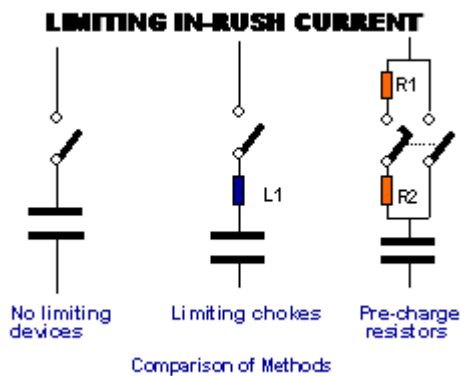
11.1.2 Inrush Current



When a PF capacitor bank encounters a change in voltage, e.g. when it is switched in, it can draw a large Inrush current of several Kilo Amps. This causes a sudden voltage dip, which de-stabilises the supply (e.g. generator can trip) and over-heats the components, reducing their useful life. The inrush current must therefore be limited.

Very often, the Inrush-current-withstanding ability of a Capacitor is not specified. Typically, one should expect this to be 100 In.

11.1.1.1 Limiting Inrush Current



The common method is to place a series choke. This needs to be a proper power inductor on a suitable core. Coiling the capacitor connecting-wire gives a few micro-Henries and can hardly be considered adequate inductance.

Pre-charge resistors can give a far better performance. However, some series inductance may still be

desirable to handle current-dump situations from charged capacitors.

11.2 Voltage

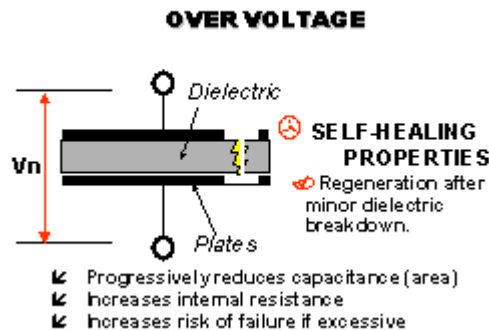
IEC831-1 and -2 specify: $V_{max} < 1.1V_n$

Moreover, the value of $1.1V_n$ may also be approached only max 8 hours every 24 hours, before considerable capacitor degradation sets in.

In addition, the same standards also say that V_{max} may go up to $1.15V_n$ for only $\frac{1}{2}$ hour every 24 hours. And a max of 200 times over the capacitor's life span.

In India, with large voltage excursions, the APFC controller can play a role in protecting the APFC components. This is far more cost-effective than over-sizing the components.

11.2.1 Over Voltage



Mild over-voltage causes excess current which heats up the capacitor. However, excessive over-voltage transients simply punch through the weakest spot in the dielectric layer. This can blow up the capacitor.

11.2.1.1 Self Healing

A voltage punch-through causes the two opposite conductor plates to short. This generates a flash of current, which melts away the PP (Polypropylene) plastic film dielectric at that spot into a large quantity of flammable gas. The aluminum layers at that spot also vapourise and settle elsewhere, clearing away the short. The self-healing converts catastrophic capacitor failure into a gradual one, with each event further reducing the capacitor area (hence the kVAR) and building up gas inside the capacitor can.

A large over-voltage can still explode the capacitor can through excessive gas build-up inside. Therefore, the can must have room inside, or a gas vent, or better still, a safety fuse built-in. This simply consists of accordion folds at the top. Under high pressure, the top bulges upwards. This stretches and snaps off one of the connecting leads inside the can, before the can explodes.

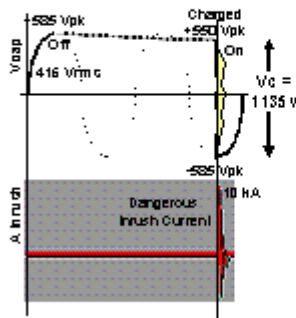
11.2.1.2 Voltage over-rating of Capacitors

One possible solution is to select capacitors rated for a higher Voltage. However, this also results in:

- Loss of kVAR, since it is directly proportional to the **square** of the voltage. A 17% drop in voltage results in a 31% drop in kVAR
- Higher kVAR, bigger Size, Weight

- Higher Cost.

RESIDUAL VOLTAGE



Connection of charged (or partially charged) capacitors deteriorates capacitors (and contactors) very rapidly.

Another alternative is to use the over-voltage trip feature of a well-designed APFC controller to protect the capacitors against over-voltages.

11.2.2 Residual Voltage in Capacitors

This condition worsens the inrush current explained earlier. It takes place when a partially discharged capacitor is re-connected. It may happen that the AC voltage at re-connect is anti-phase with the charge already on the capacitor, giving a kilovolt surge. The inrush current damages both the Capacitor and the contactor.

It is important to remember that loose contacts, contactor chatter, improper switching or hunting with unsuitable APFC Controllers, etc give a similar problem.

The residual voltage problem is also worsened when users aim for very fast, rapid APFC correction. Rapid switching is a myth for normal applications, because it is only the average PF at the end of a month that matters.

Properly sized discharge resistors are necessary to discharge the capacitor fast enough. The safety bleeder-resistors that capacitor manufacturers place may take 15 minutes to discharge the capacitor, too long for APFC applications.

11.2.3 Resonance

Capacitors in parallel with inductive loads, pave the way for resonance in the electrical system. Resonance generates oscillations in the supply feeder, sometimes resulting in large over-voltages.

The susceptibility to resonance and the resonance frequencies depend on the distribution of impedances in the electrical system. High harmonics (%THD) from non-linear loads can trigger and worsen resonance.

11.3 Temperature

IEC 831-1 and -2 state the ambient temperature limits of the Capacitor as shown in the Table.

The Maximum Temperature permitted for a 1 Day Average and for a 1 Year Average show the heavy

Temperature Class	A	B	C	D
Peak Rating °C	40	45	50	55
1 Day Avg. Max °C	30	35	40	45
1 Year Avg. Max °C	20	25	30	35

influence of temperature on the capacitor lifespan.

Arrhenius' Law for capacitors says that:

- Life expectancy **DOUBLES** for every 7°C drop in temperature. Or,
- Life expectancy **HALVES** for every 7°C rise.

Consider an example for life expectancy for a Class D capacitor rated for 55°C at continuous exposure to different temperatures:

- 20,000 hours at 55 °C (2.3 years)
- 40,000 hours at 48 °C (4.6 years)
- 80,000 hours at 41 °C (9.1 years)

12 APFC Panel Design Critical Factors: Contactors

Contactors are the “Hands” of the APFC Panel, which physically switch capacitors in and out of the circuit. The contactors must be rated for capacitor duty, which means they have been designed for Inrush current. Thus, they are more expensive than normal contactors.

While an inrush current rating of at least 100In is expected, few contactor manufacturers actually publish an inrush current spec, since it is so difficult to test and guarantee.

Poor contactors can affect capacitors through contact re-connection, chattering, welding, burning, etc.

12.1 Inrush Current

While capacitors are responsible for drawing inrush currents, the contactors are also severely affected.

The Contactor Peak Current limits:

- Vary with Brand, due to electro-mechanical factors
- Are often NOT specified. But the peak ratings are lower than actual capacitor inrush
- **Are not proportional to rated current, with increasing**

		20 kVAR	40 kVAR	60 kVAR
Contacto r	In	30A	60A	90A
	Ipeak	<i>1400A</i>	<i>2500A</i>	<i>3000A</i>
Capacito r	In	29A	58A	86A
	Ipeak	<i>2900A</i>	<i>5800A</i>	<i>8600A</i>

capacity. Notice that with increasing capacity, the Capacitor maintains an inrush rating of 100In. However, the contactor rating drops from 46In at 30A to 33In at 90A.

- Must be carefully considered

12.2 Number of Operations

Contactors have an electrical life of around 80,000 to 100,000 operations. The mechanical (no load) life can be much higher. To minimise the lifetime cost of contactors:

- The APFC controller must be designed and programmed for no Hunting,
- The control settings and algorithm must ensure the lowest number of operations

The APFC controller must also offer adequate protection:

- Contactors must be immediately switched off in case of mains drop-outs and micro-interruptions.

13 APFC Panel Design Critical Factors: Cabinet

13.1 Size

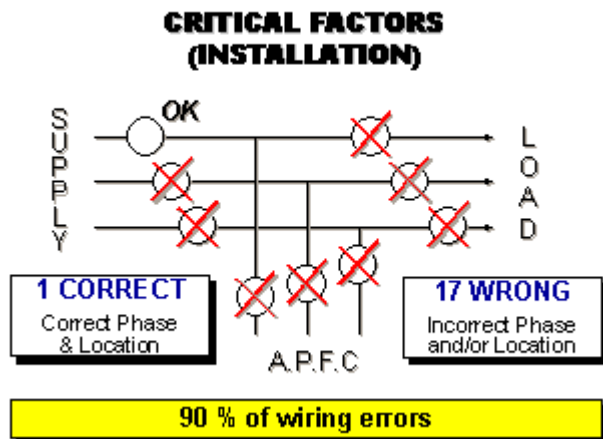
An efficient layout is necessary to keep the components close together in one cabinet, and reduce wiring lengths. This also reduces wiring errors and failures. A metal partition can provide safety and some shielding to the control section. The panel must be the largest size to ensure heat dissipation. This also provides room for some future expansion, to increase the kVAR. However, larger panel also means:

- Larger Space occupied
- More Weight
- Higher Cost

The Panel must also be tight against external dust and pollution. However, this also means:

- Reduced air exchange
- Higher Internal Heat

13.2 Forced Cooling



Therefore, for a compact panel to run efficiently:

- Forced Air Cooling is necessary to extend the life of Capacitors and Contactors
- Thermostat Control reduces blower consumption and increases life of fan

The APFC Controller should provide a Fan Control output. This way, the blower is also protected during

abnormal conditions.

14 APFC Panel Design Critical Factors: Installation

The APFC Panel must be mechanically sound and provide quick service access. Wiring correctness is critical. The APFC controller is wired wrongly in 90% of the cases. There are 17 wrong locations (including CT S1 S2 reversal) and only 1 correct location for sensing the signal.

The APFC controller must have:

- Wiring diagnostics Indicators
- Manual Modes to test each bank

This reduces the occurrence and cost of service field visits, lowering lifetime cost of the panel.

15 APFC Panel Design Critical Factors: Usage

15.1 Manual Switching

Manual Switching is useful during Testing. However, improper or frequent Manual Switching is a cause of Panel Failure. In fact, the easiest way to blow a capacitor is to just connect a push-button switch to operate the contactor manually. Just rapidly operating the push-button manually, 15 or 20 times, will explode the capacitor! Please refer the problems from Inrush and Residual Voltage described earlier. The APFC controller manual mode must provide the necessary safety interlocks. For this reason, a good APFC controller can be cost-effective even for purely manual operation.

15.2 Periodical Inspections

Monthly Dust removal, cleaning and tightening of all connections will prolong the life of the panel considerably. At the same time, the capacitors could be manually operated. Change in

PF indicated by the APFC controller on individual capacitors under Manual mode can be logged. Alternatively, capacitor current could also be measured with a tong-tester. This is a clear indication of reducing capacitor kVAR. Weak capacitors should be promptly replaced before catastrophic failure.

Without Periodical Inspections, panel problems are often under-estimated because the initial symptoms are silent and the panel is pressed into service 100% of the time.

16 Desired APFC Benefits: In Design

Programmable APFC Controller functions enable the panel manufacturer to adapt the design and effect some last-minute tuning:

- Programmable Intervals to slow down the switching as much as possible, to suit load dynamics
- Programmable Logic. Universal (Geometric) is most efficient for most applications. Linear and Ring switching sequences are needed for some specialized applications. Linear suits very accurate compensation of slowly varying loads. Ring switching precisely equalizes wear on capacitors and contactors, eg in HT applications.
- Automatic Functions with Alarms and Tripping
- Fan Control with built-in thermostat
- Extension or Disabling of Alarms in special cases
- Intelligent Functions for maximum protection

17 Desired APFC Benefits: In Contracting

Installation must be simple:

- Wiring Test to detect wiring errors
- Reliable pin-pointing of wiring error

These features on the APFC controller could save field-trip costs, by allowing diagnostics over the telephone.

18 Desired APFC Benefits: On Equipment

Intelligent APFC Controller Functions:

- Reduce wearout,
- Reduce Incidence of Field Failures
- Protect Equipment
 - Switch-off banks on micro-interruptions and mains faults
 - Ensures re-connection time under all working modes
- Safeguard and Increase equipment Life
 - Switch-off for excessive V, A, °C
 - Intelligent Alarm Functions

18.1 Desired APFC Benefits: At Site

- Prevent Improper Manual Switching
 - Clear Alarm until discharge time has elapsed to prevent false alarms
 - Fool-proof manual control
 - Disable re-connection prior to proper discharge
- Alert on Malfunctions
 - Alert on system failures reducing ability to achieve PF (fuses blown, banks out of service, contactors welded or open, etc)
 - Memory indication of past Events
 - Alert on likely PF penalties (irregular compensation)
- Simplify Inspection
 - Manual Modes to simplify equipment check-up

19 APFC Alarm Functions

19.1 Benefits

A well-designed APFC panel must incorporate effective Alarm Functions:

- A “Must” on larger equipment to protect value
- A Safety Tool in critical installations
- A significant added value for equipment

The benefits:

- Vital for Equipment Integrity
- Reduces risk of severe damage
- Likely to extend equipment life
- Reduced need for maintenance
- Equipment Design Optimisation

19.2 Suitable Alarms

The alarms must

- Have clear indication of specific conditions
- Automatically re-start upon return to normal conditions

Suitable Alarms are:

- Over-Current
- Over-Voltage
- Over-Temperature

- Irregular Compensation
- Low-volt Release
- Low Signal Release

20 Conclusion

Automatic Power Factor Control improves energy efficiency. This is both a significant competitive edge in the global context as well as a national priority.

Well designed and well used APFC panels further add to that efficiency by reducing the lifetime cost of the panel to the end user.

This paper has examined simple and effective steps to reach this goal.