Harmonic Resonance – Its Origin and Some Common and Uncommon Measures for Preventing and Managing it

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ABSTRACT

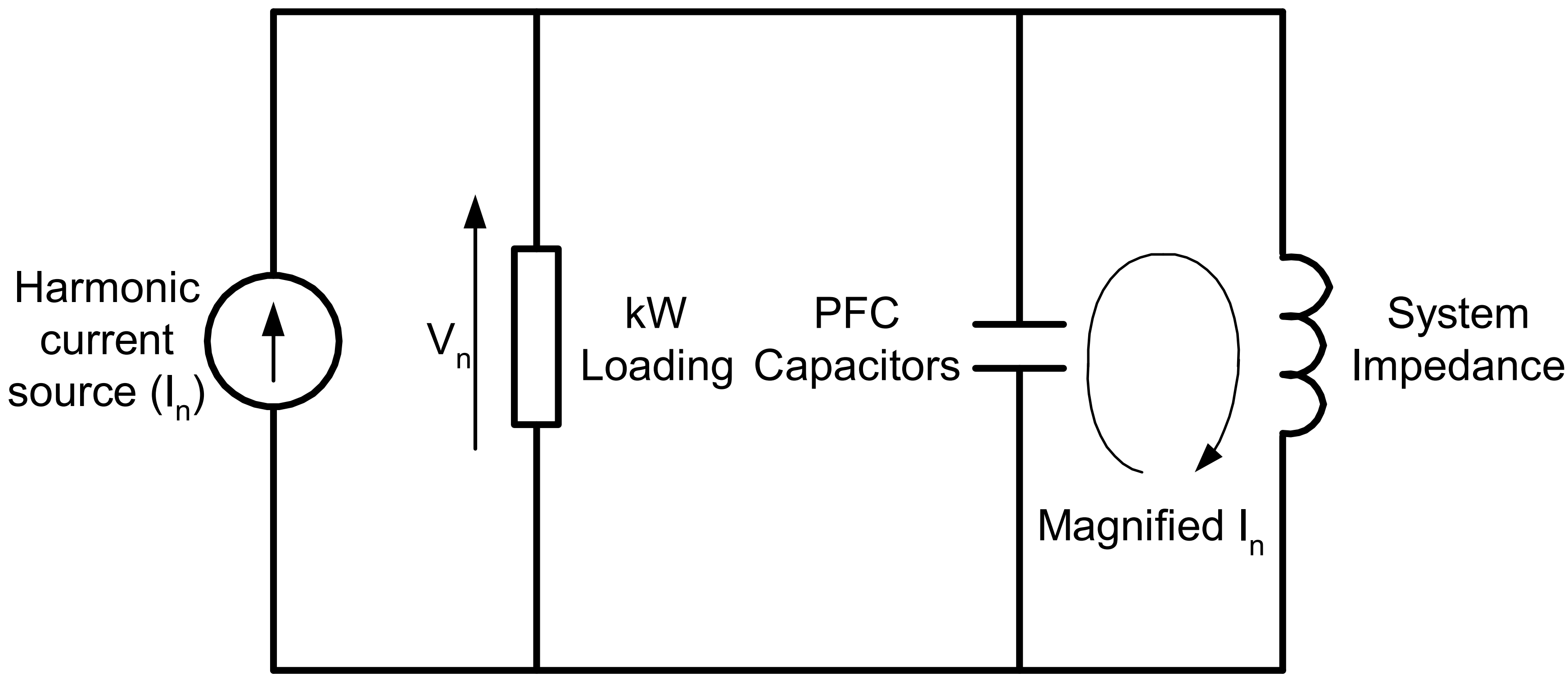
Harmonic resonance is a major power quality issue. It aggravates the problems created by harmonics like electrical breakdowns, distortions in performance of electrical and electronic equipments and systems, spurious tripping incidents, erratic operation of controls. These problems during resonance occurrence get amplified and can cause accidents and become fire and safety hazards. Harmonic resonance is fortunately a self-correcting phenomenon and accelerates failure of one or more capacitors thus taking the system out of resonance. Efforts are to be made to facilitate self-correction but in actual practice this is not done. A Capacitor failure should act as a warning indicating possibility of a major mishap but many times instead of properly investigating the cause of a capacitor failure it is promptly replaced like a consumable. This is likely to result in reemergence of harmonic resonance. The most common cause of harmonic resonance is indiscriminate use of capacitors. Likewise, most common solution to avoid resonance is use of 7% detuned reactors in series with power factor correction capacitors. Power Quality study is basis for design of passive, active or hybrid solutions for comprehensive solution for mitigating harmonics, improving power factor besides ensuring elimination of resonance. However, pending comprehensive resolution the harmonic resonance can be tackled by breaking the existing balance between capacitive and inductive impedances with removal or addition of some capacitors in the affected system. Software like ETAP, Cyme etc are available to conduct resonance study for greenfield or running projects. Peculiarities of LV and MV systems and specific resolution measures are discussed. The article discusses in detail with illustrations, the mechanism of resonance occurrence, techniques for resolving it, various preventive measures, and recommendations for managing harmonic resonance.

How Harmonic Resonance Occurs

The next slide shows load and power factor correction capacitors connected across the transformer. The loads today are predominantly nonlinear and cause harmonics which are represented by harmonic current source parallel to the load.

The capacitors act as sink to harmonic currents as the impedance offered by capacitors to harmonic frequencies is low. The harmonic currents flow through the transformer secondary winding. The harmonic currents reflect in the primary winding of transformer and get further exported right up to grid through intermediate transformers. The capacitive impedance and indicative impedance values of the network are equal at a particular frequency and if this frequency happens to be the frequency of a harmonic present in the system, then there is a resonance at this harmonic frequency. This causes amplification of resonant harmonic current. The next slide shows a plain capacitor causing Harmonic resonance amplifying harmonic current. The amplified harmonic current can be dangerously high and overloads the electrical installation. A capacitor normally is the first casualty in a harmonic environment due to its low impedance to harmonic frequencies. Repeated failure of capacitors is indicative of resonance occurrence in the system.

How Harmonic Resonance Occurs



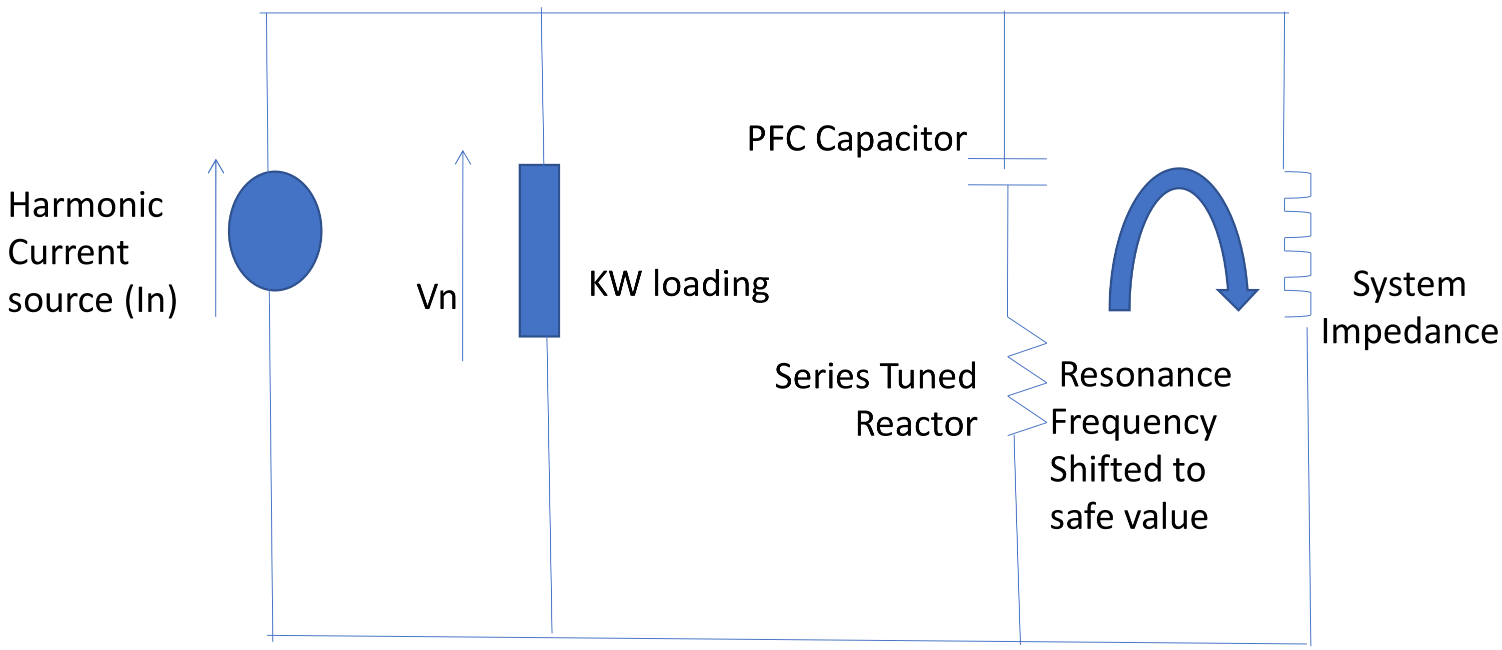
Most Common Measure of Preventing Harmonic Resonance

The most common measure of preventing harmonic resonance is to connect 7% detuned reactors in series with power factor correction capacitors. The tuning frequency of a 7% reactor is 189 Hz. Next slide shows a detuned reactor which is usually a 7% reactor which shifts the resonance frequency to a safe value. The 7% detuned reactor works in most cases and avoids harmonic resonance.

A 7% detuned series reactor besides avoiding resonance at an unsafe harmonic frequency also does the job of limiting capacitor inrush current. It partially mitigates 5^{th} harmonic and to some extent other higher order harmonics.

A 7% detuned reactor should not be taken as a universal solution to avoid harmonic resonance. Sometimes harmonic resonance is observed even after using 7% detuned reactor. Wherever this is observed use of 14% detuned reactor is found to positively avoid harmonic resonance. As 14% detuned reactor is tuned close to 3^{rd} harmonic at 133Hz, it mitigates mainly third harmonic.

Series Reactor Shifts Resonance to a Safe Frequency



Some More Passive Solution Options

Fifth harmonic is usually the most prominent harmonic in power systems followed by seventh harmonic. Third harmonic is observed mainly in installations with significant single-phase loads. It is to be noted that the detuned reactor can cause another harmonic resonance below its tuning frequency. The reason for using 7% detuned reactor with tuning frequency close to 5^{th} harmonic is that fifth harmonic is the most significant lowest order harmonic and there is no possibility of it inducing another harmonic resonance. If passive solution is attempted for mitigating more harmonic frequencies in addition to 5^{th} harmonic, such as 7^{th}, 11^{th} etc then precautions are to be taken to ensure that there is no unfavorable harmonic resonance caused by these reactors.

Variation of System Impedance at different Frequencies

The next slide shows variations of system impedance values at different frequencies.

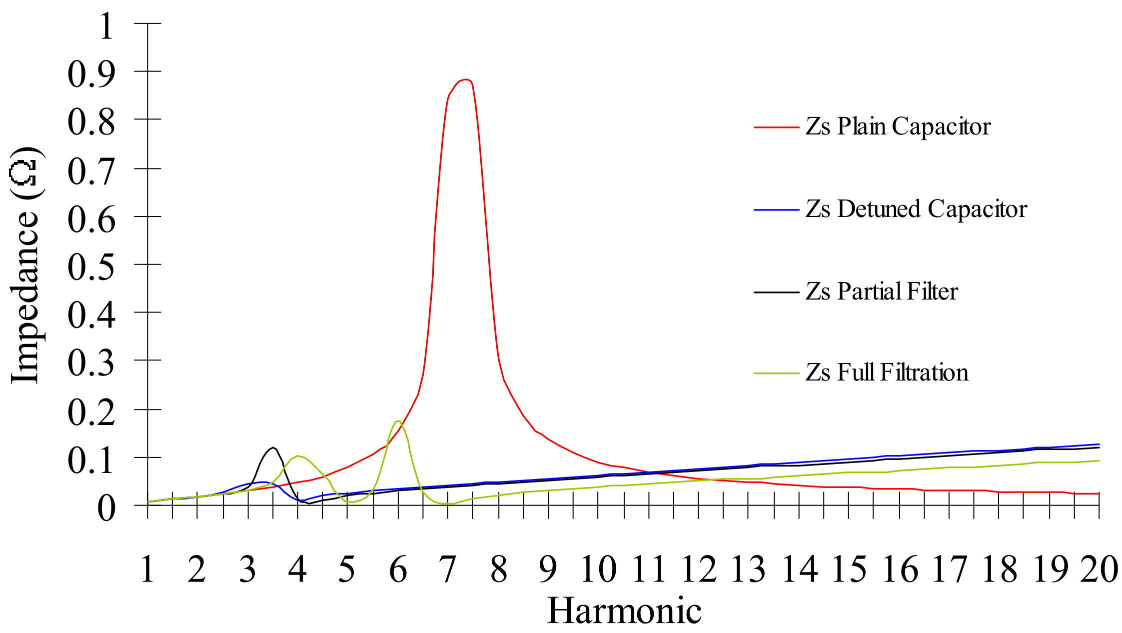
The frequency where system impedance is maximum is the resonance frequency. At low frequencies Power System Impedance is determined by the impedance of the Transformer and the Transmission lines. At Higher frequencies impedance of Power factor correction Capacitors is the dominant factor in determining the system impedance value.

Harmonic Resonance is indicated at 7th Harmonic as shown in red curve when plain capacitor is used.

The 7th harmonic is usually present in the system due to large number of 6 pulse converters in use today, thus this gets amplified. The resonance point shifts to somewhere at a safe frequency say between 3rd and 4th harmonics when 7% detuned reactor is used in series with power factor improvement capacitor as shown in blue curve. This is a safe point as there is no harmonic present at this frequency and thus there is no question of harmonic amplification.

Maroon curve shows impact of reactor tuned closer to 250 Hz as compared to 189 Hz and does a better filtration. The green curve shows two detuned reactors tuned respectively for 5th and 7th frequencies for still better filtration. Harmonic resonance is avoided in both cases.

System Impedance and Harmonic Frequencies

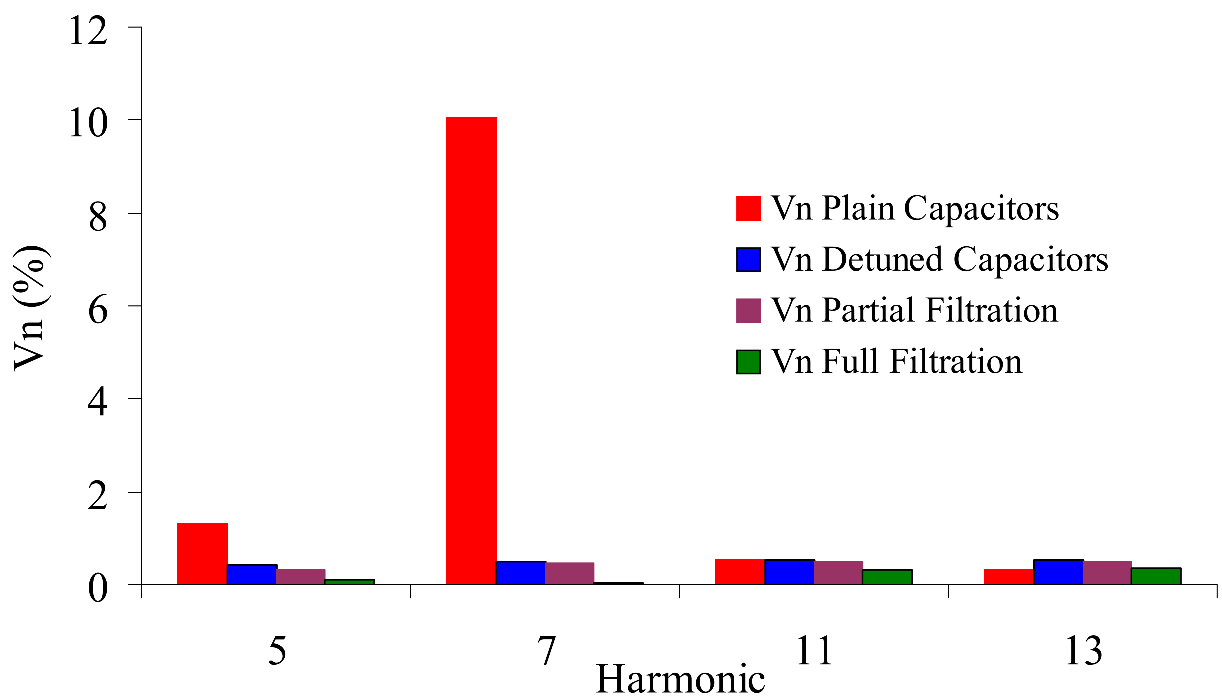


Voltage Distortion Caused by Various Passive Solutions

The next slide shows a typical case of impact of various passive solutions on the voltage distortion caused by them.

Plain capacitors in the case under observation cause maximum voltage distortion shown in red as harmonic resonance is observed at 7^{th} Harmonic. 7% Detuned reactor tuned at 189 Hz shown in blue brings down the voltage distortion significantly as resonance is eliminated but filtration is nominal. A reactor tuned closer to 250 Hz shown in maroon for partial filtration brings down the voltage distortion further and does better filtration too. Multiple reactors tuned for 5^{th} and 7^{th} frequencies for almost complete filtration shown in green bring down voltage distortion to negligible level and provide almost complete filtration.

Comparative Impact of Harmonic Resonance Solutions



Calculation of Detuning Frequencies

DETUNING FREQUENCIES

- For series LC Detuned Filters, the tuning frequency (Ft) is set below the lowest Harmonic with remarkable amplitude which is normally the fifth Harmonic

$$F_t = \frac{\mathrm{f}}{\sqrt{\frac{p}{100}}}$$

Where f = fundamental frequency P = Detuning Ratio in percentage

- For 7% Detuning Ratio

$$F_t = \frac{50}{\sqrt{\frac{7}{100}}} = \frac{50}{\sqrt{0.07}} = \frac{50}{0.2645} = 189 \text{ Hz}$$

Some Critical Consequences of Harmonic Resonance

All the adverse effects of harmonics manifest in a magnified way during harmonic resonance. A resonance condition in an electrical network is akin to a short circuit condition with uncertain and unknown level of severity. There is no dead short circuit and the heavy currents do not activate short circuit protections, nevertheless, currents can be large enough to cause excessive heating in the associated circuits with consequential damage to the circuit elements viz. cables and switchgear and more particularly to capacitors. The reason for most of the electrical fires is cited as an electrical short circuit. However, the possibility of harmonic resonance leading to such fire incidences cannot be ruled out.

Following are some of the practical observations about consequences of harmonic resonance:

1. Accelerated failure of capacitors, electronic cards, thyristors, reactors, and various other electrical and electronic components.
2. Tripping due to maloperation of thermal protections like thermal releases and bimetal relays.
3. High metering errors which at times can be to the extent of meters getting blanked out.
4. A plant operating on own generation in an Iceland mode experiences heavy voltage distortion which does not allow its loading beyond a fraction of its capacity.
5. An extreme consequence could be an electrical fire as shown in next slide.

Worst Case Scenario in the event of Harmonic Resonance

In worst case...

Frequency of Harmonic Resonance

$$N_{res} = \sqrt{\frac{Scc(kVA)}{kVAr}}$$

SCC – Short Circuit Capacity
KVAr- Connected Capacitors
Nres- Resonance Frequency

Some Uncommon Measures for Preventing Harmonic Resonance

Removal or Addition of Some Capacitive KVAR

The previous slide shows a relation between short circuit KVA and Capacitor KVAr in the system. The square root of the ratio between short circuit MVA and MVAR of capacitors connected in the system gives a number Nres which denotes the harmonic frequency where the resonance takes place.

For 1000 MVA source and 20 MVAR capacitors Nres is square root of 1000/20 i.e., square root of 50 which is close to 7. Thus, the harmonic resonance occurs at 7th frequency. This is an unsafe frequency as 7th harmonic is normally present in the system. When harmonic resonance is noticed in a system the immediate interim solution can be removal of some capacitors or addition of some capacitors to bring the system out of resonance. However, it should be noted that this is to be resorted to only as a stop gap solution and the normal passive, active or hybrid solutions should follow.

Another Uncommon Measure for Preventing Harmonic Resonance

Correcting Configuration of Linear and Nonlinear Loads on a Transformer

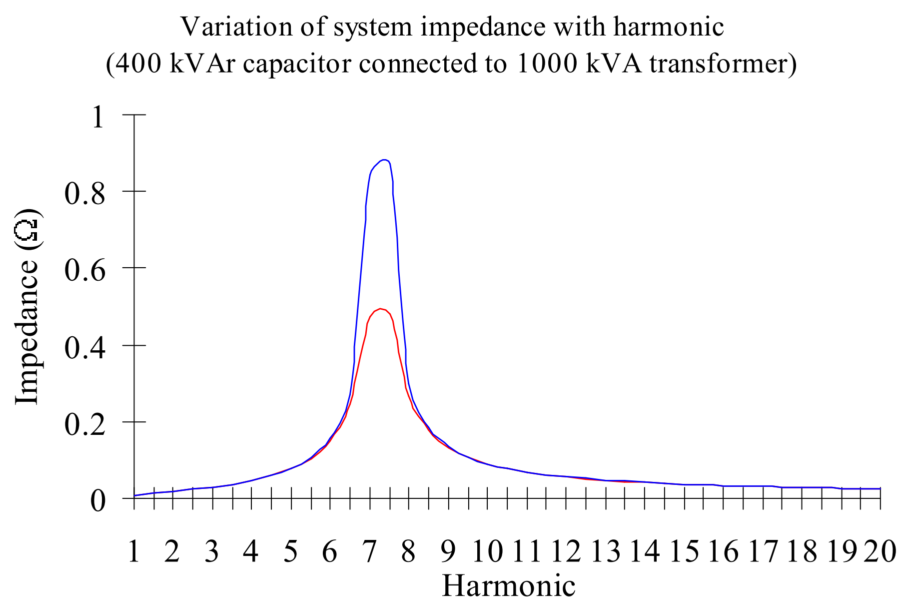
It is observed that many times linear and nonlinear loads are segregated in a way where nonlinear loads are put on one transformer and linear loads are put on another transformer. However, a better configuration of loads is to have each transformer with combination of linear and nonlinear loads. This helps in reducing the severity of harmonic resonance as shown in next slide. The blue curve where the linear load content on the transformer is nil indicates a severe harmonic resonance. The red curve indicates a milder harmonic resonance when 400 KW nonlinear load is replaced by linear load. This measure is not normally easily feasible in a running plant, but it is recommended to be considered during design stage.

Judicious Combination of Linear and Nonlinear Load on a Transformer Reduces Impact of Harmonic Resonance

Blue Curve Shows Linear Load = 0 (All Load is Nonlinear)

Red Curve Shows Linear Load = 400 KW

Impact of Harmonic Resonance Reduces with Addition of Linear Load



Managing Harmonic Resonance Present in a System

As explained above efforts are made to avoid occurrence of harmonic resonance but harmonic resonance occurs despite all efforts for variety of reasons such as indiscriminate use of plain capacitors, faulty design of harmonic reactors, dynamic load conditions, deterioration and failures of capacitors and reactors etc.

Once the harmonic resonance occurs efforts are to be made to bring the system out of resonance as the adverse effects as explained above can be dangerous. Many times, it is observed that till the adverse impacts of resonance become unmanageable systems keep running with increased failures and problems.

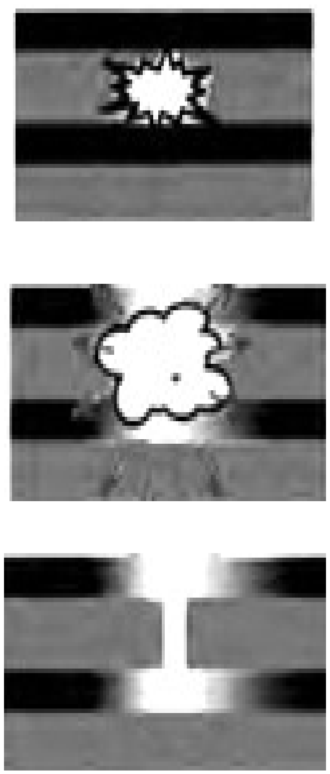
Harmonic Resonance is a Self-Correcting Phenomenon

Once the harmonic resonance occurs the immediate remedy is to bring the system out of resonance. Fortunately, resonance is a self-correcting phenomenon. The capacitors draw heavy current under resonance condition and in the process one or more capacitors fail and bring the system out of resonance as the balance of inductive and capacitive impedance is disturbed. Thus, capacitor acts like a fuse during a resonance occurrence and saves the installation from a bigger damage. Efforts are to be made to facilitate the capacitor failure under a resonance condition. The use of MPP capacitors with built-in safety features like over pressure interrupter mechanism, segmented film, self-healing, and contact ring for solderless end connections are recommended for low voltage applications as they provide a safe mode of failure to power capacitors under heavy resonance induced currents. Further, MPP capacitors have open circuit mode of failure which is safe. The self-protective nature of self-healing capacitors having safe mode of failure provides much needed protective cover to the system in the absence of any defined external protective mechanism when resonance induced heavy currents flow through capacitors.

Self-Protective Features of MPP Capacitors

Self protective features of MPP capacitors are described in next four slides. As described in previous slide MPP capacitors offer natural self protection against harmonic resonance without need of any external safety. They isolate themselves safely during resonance and save installation from a bigger damage. Capacitor failures can be an indication of harmonic resonance and thus the failures should be investigated. Capacitors are not to be treated as mere consumables and replacements should be done judiciously. Next four slides describe the self-protective features of MPP capacitors.

Self Protective Features of MPP Capacitors – Self Healing

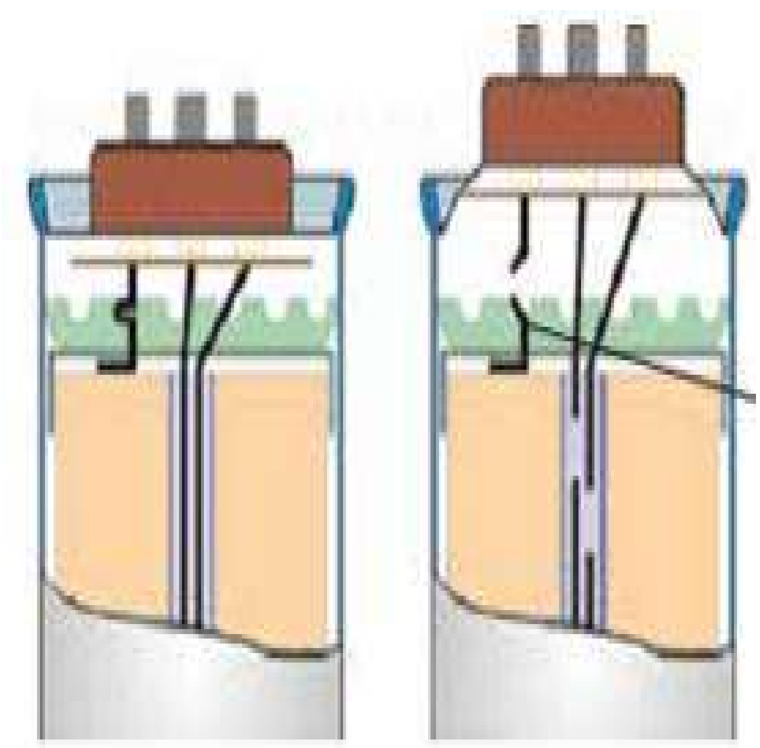


Self-Healing MPP Film: Any localized heating due to heavy surge currents is automatically cleared and the faulty section is isolated by the self-healing process.

Self Protective Features of MPP Capacitors-Segmented Metalized Film

Segmented Metalized Films: If there are several occurrences of self-healing process in a small, metallized film area due to heavy currents then self-healing action alone may not be able to cope up with the situation due to the enormous amount of energy produced and may result in failure of capacitor. This is prevented by segmented film construction which restricts the fault within the affected segment area and the affected segment is isolated and the fault is not allowed to spread throughout the film. The capacitor life is thus enhanced.

Self Protective Features of MPP Capacitors-Overpressure Interrupter Mechanism



Three Phase Overpressure Disconnector: There is a three-phase mechanical fuse incorporated in each capacitor. If there is an excessive internal pressure development due to overloading or at the end of service life of capacitor, then the mechanical fuse safely isolates all the poles from supply thus avoiding any unsafe condition during failure.

Self Protective Features of MPP Capacitors-Contact Ring for End Connections

Contact Ring: The Contact Rings made from special alloy and having pointed teeth are used for secure end connections with spot welded connection to the internal leads. This is a solder free design which avoids damaging the winding at manufacturing stage due to overheating during soldering process. It also provides mechanical stability for smooth operation overpressure interrupter mechanism.

Why APP Capacitors are to be Avoided in LV Applications

APP capacitors have a short circuit mode of failure which is unsafe. APP capacitors continue to remain in circuit in the absence of any built-in safety features under resonance conditions which may lead to dangerous consequences of fire, explosion, accident etc. It is a worldwide practice not to use APP capacitors in LV applications mainly out of safety concerns. In MV and HV applications use of APP capacitors is not a safety concern as the unbalance protection takes care of isolating the capacitors under resonance conditions also. The resonance causes failure of internal capacitor elements in APP capacitor units which initiates unbalance condition and activates unbalance protection to isolate the capacitors.

Though MPP capacitors for MV application have been developed and should be preferred for MV and HV applications as well but these are still not commercially viable for widespread use.

Some Recommendations to Manage Resonance

Use of Plain Capacitors to be avoided

This is by far the most common cause of harmonic resonance. If capacitors are used with detuned reactors the harmonic resonance is eliminated to a large extent.

Multi Tap Detuned Harmonic Reactors to be used

This provides an opportunity to select the tap suitable for particular site in case harmonic resonance is observed.

Power Quality Audits to be Conducted

Power quality audit is to be conducted regularly to check healthiness of system. PQ audit is also recommended when increased failure of capacitors is observed as it is likely to be indicative of harmonic resonance. Once the status of power quality is known corrective actions can be worked out such as updating the harmonic reactors design.

Some Recommendations to Manage Resonance – Continued

Resonance Study to be conducted for a Green Field Project
The ETAP/CYME Software can be used to conduct resonance study to confirm suitability of reactive power solutions being employed.
Neutral Strengthening to be done where Single-Phase Load is Sizeable
Single Phase loads cause zero sequence harmonics which flow through neutral.
The neutral also carries unbalance current of the phases. These two factors together can cause neutral current to be two times the phase current. The neutral loading can increase further if a harmonic resonance occurs. Thus, entire neutral circuit needs to be strengthened. All IT installations use five core power cables with two cores reserved for neutral. This practice needs to be followed by other installations like hotels, hospitals, multiplexes, malls, large commercial and residential complexes etc.

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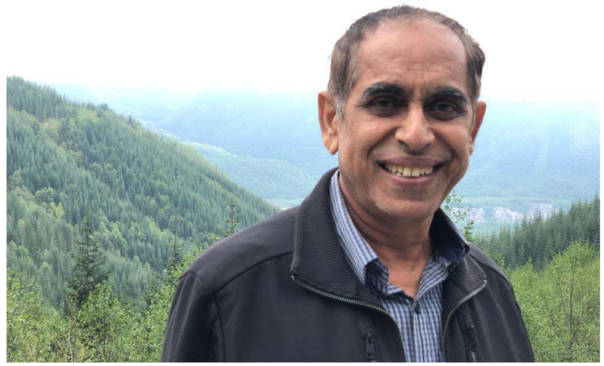

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Thank You…