Power Quality (PQ) Improvement Systems on LT distribution: Benchmarking of PQ and Various methods & merits.

Abstract

Various aspects of Power Quality need to cater to issues like:

- Voltage Sags and Swells.
- Momentary mains cycles loss.
- Voltage surges and High frequency noise / disturbance (sometimes called as transients or glitches)
- Current surges and high fluctuation of load current (normally reflects onto voltage problems)
- Current Harmonics and consequential Voltage Harmonics.
- Inter-harmonics on Current and Voltages.
- Neutral floating or shifting.
- Earthing Problems.
- Power Outages and effect of Auto-Reclose system.
- Load Shedding (Specifically with countries where demand is much higher than generation)
- Power frequency Variations.

And some issues that are indirectly related to Power Quality:

- Reactive Power Compensation issues.
- Load unbalance between the phases and Neutral loading.
- System Resonance – Parallel and Series.
- Maximum Demand control (kVA demand and kW demand).

There are widespread efforts to make a system that is able to take care of all these issues through "Unified Power Quality Compensation System". Unfortunately, the issues are many and each one requires a specialized approach to take care of them. Additionally, if one tries to take care of all the issues in one system, it causes the system cost to go up causing economic issues.

These PQ issues too are dependent upon the Electrical Load types. Various types of industries, commercial complexes, urban household loads, rural electrical load requirements etc. are causing PQ issues of various types. But all the issues are never seen to be present at every LT installation. Only, few of the above mentioned issues may be present on a specific given installation. Thus, it is seen that instead of usage of Unified Control System which does not fit into economics, most of the installations prefer to cater to the specific PQ issues. This necessitates the usage of various systems that caters to one or few specific PQ issues present on a given specific installation.

Most of the Power Quality Audits, concentrate on measurement and the specific issues. Unfortunately, a very less emphasis is seen in such audit reports on the type of systems to be used for taking care of the issues. Thus, concerned personnel have no option but to depend upon the various manufacturer's for supply of such systems. Most of the suppliers to suit their product range give various glorified pictures. The best approach for every installation has to first undergo the "PQ Benchmarking" process first by identifying the issues present on the installation. Then, has to specify the "Guaranteed Technical Particulars" (GTP) of the product they wish to install for taking care of the PQ issues. After defining the GTP, the specific supplier's products are to be evaluated depending upon the benchmarking requirements. This can avoid purchase of system with unwanted features as well as economics is maintained.

For a specific installation, Benchmarking is extremely important. Some PQ issues may be present on the installation but all of them need not be necessarily addressed; as these may not cause any undesirable effect on the specific installation. The issues that really cause the problems too can be neglected if brought within specific limits. For this purpose, simple approach can work many times as compared to usage of sophisticated PQ compensation equipments. Unfortunately, the PQ compensation equipment manufacturers too are many times approached for such benchmarking process and such benchmarking created is normally to suit the specific manufacturer rather than the specific system needs.

If the Benchmarking is generated based upon the installation requirements, the specific type or types of system/s specifications can guide the user to select the right type of system for their need. The approach of this Technical Paper is to create awareness about the right approach towards PQ needs and to introduce various types of systems that can be used for specific need of PQ issue/s.

In this technical paper, author wishes to highlight the benchmarking approach and various types of systems for their applicability towards the earlier defined PQ issues along with their merits and demerits.

Now days, there are various types of systems that are available for taking care of more than one PQ issues. These are normally the part of FACTS product family. Still, the old approach of passive component approach is still economical and can bring the results set by benchmarking in many electrical installations.

The various systems for Voltage stability gives specific description about the systems like:

- Solid state voltage stabilizers
- Servo control stabilizers
- On load Tap Changers for Transformers
- CVT – Constant Voltage Transformers.
- UPS – Uninterrupted Power Supply systems.
- Series boost – buck converter.
- High speed Thyristorised Power Factor Correction (reactive power compensation) system.

The types of approach used normally for Mains Cycles loss and momentary Power Outages with Auto Reclose systems are:

- Ferro resonant Transformers.
- UPS – Uninterrupted Power Supply systems.
- Synchronous generators with fly-wheel.

For Voltage Surges and transients:

- Lightning Arresters.
- Usage of Earth conductor over open distribution lines.
- Usage of MOVs (Metal Oxide Varistors) – High Power and normal grade.
- Capacitor filters, Low pass filters like T, L and Pi filters.
- Zero Voltage Capacitor switching and synchronous switching of loads.

- Shielding with differential and common mode disturbance filtering like low impedance power conditioning.

For Current and Voltage Harmonics and Inter-Harmonics:

- Passive L-C shunt tuned and partially tuned filters
- Low pass filters for 6-pulse converter type systems like AC/DC drives & UPS.
- Usage of 12 pulse converters.
- Z-Winding Transformers for taking care of triplen harmonics.
- Active filters – Static Synchronous Compensators (STATCOM)

For Neutral Shifting and Earthing:

- Earthing grid enhancement.
- Usage of Isolation Transformer.

Additionally, for indirect issues of Power Quality, The systems that are used:

For Reactive Power Compensation:

- Usage of Auto PF correction systems (Normal speed and High speed using thyristorised switching) or Static VAR correction systems.
- Static Condensers (STATCON).
- Usage of appropriate rating capacitors.

For Unbalanced Loading:

- Passive Load balancing system – Fixed and Dynamic.
- STATCOM system also offers this additional feature.
- Individual phase Power factor correction system.

System Resonance: Such phenomenon are quite rare on LT distribution. Still, in case of such phenomena seen, approach is towards adjustment of passive elements like Capacitors and Reactors values and positioning in electrical system.

Maximum Demand Control:

- Usage of maximum demand controller system.

Load Shedding (specifically with countries with wide –ve gap between supply generation and demand.
The issue in such case is complex and depending upon the need, various types of systems have been designed in such countries. This paper also briefly looks into such system design and the related specific issues.

As can be seen in the systems listed above, some of the systems are appearing in multiple types of PQ issues. Thus, termed as an Unified approach.

Details of all the stated issues in this Abstract are looked into the main technical paper.
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Power Quality (PQ) Improvement Systems on LT distribution: Benchmarking of PQ and Various methods & merits.

The term – "PQ" on the electrical supply system has number of aspects to look into. The solutions to the various aspects of PQ are different for different aspects. These are depending upon the nature of the PQ issues.

Additionally, the electrical supply systems have various needs in terms of PQ depending upon the application requirement. Very little is spoken about the issues faced by industries as well as other varieties of electrical consumers, which primarily uses the equipments running on the LT supply system. (Voltage range of 110Vac to 1000Vac). Every type of equipment working on electricity is designed with keeping in mind the level of adversities on electrical supply system. Thus, for such equipments to work satisfactorily, the PQ benchmarking should be at better level than the equipment design parameters for such adversities (PQ issues) on supply system.

Most of the standards talk about maintaining the PQ standards such that whatever one consumer of electricity does with regards to creating any adversities on electrical supply system, the other consumers should not get affected. Normally, the issue is always discussed at PCC (Point of Common Coupling). This is the view point from supply systems utility that has primary responsibility of giving the clean power to their consumers. But, what happens within a specific installation for a consumer is always left to the discretion of the consumer provided such consumer is not creating the PQ problems for other consumers. Thus, primary target for the consumer is always to meet the requirements as specified by electricity supply utility or is specified by certain internationally known standards. Still, the electrical consumers after meeting this requirement give little attention to their internal needs on PQ standards. This unknowingly causes losses to them.

It's important for consumers to know the benchmarking requirements of PQ depending upon the need of their installation. Sometimes, the needs to improve PQ may not exist at all if the PQ issues that may be existent on supply line may be well within the limits of the benchmarking standards. Sometimes, if consumer meets the requirements of PQ for supply utility needs, the internal benchmarking standards still can be exceeded. In such case, even though there is no pressure from electrical utility, one has to look into improvement of PQ within the consumer area so as to reduce the in house losses caused. Thus, in-house benchmarking on PQ issues is an important topic, even though in most of the cases it is neglected.

The approach towards PQ benchmarking with LT distribution within an installation is best carried out at the time of new installation where one can have a good control over the electricity consuming equipment specifications and is aware about the PQ issues that are present from Supply Utility side.

But, with the consumers having existing installed equipments, the equipment change for meeting the benchmarking is not a viable proposal due to economic aspect. In such case, depending upon the needs, the benchmarking of PQ improvement equipment selection based upon the exact needs seems to be the right approach.

First, the benchmarking methods can be discussed herein and further the various equipments that can be selected based upon the benchmarking needs and equipment capabilities can be discussed.

LT Electricity Consumer PQ Benchmarking process:

The benchmarking process within a specific installation is normally governed by the various factors like:

- Governed by supply utility. Measured normally at point of supply (or metering point).
- Governed by the equipments used by consumer. The equipment specifications with regards to PQ requirements.
- Processes for manufacturing goods quality control within the industry. Mainly the process reliability.
- Other factors such as Human safety and data communication requirements.

Based on these factors, the minimum benchmarking needs can be defined with regards to various issues of PQ such as:

- Voltage Sags and Swells.
- Momentary mains cycles loss.
- Voltage surges and High frequency noise / disturbance (sometimes called as transients or glitches)
- Current surges and high fluctuation of load current (normally reflects onto voltage problems)
- Current Harmonics and consequential Voltage Harmonics.
- Inter-harmonics on Current and Voltages.
- Neutral floating or shifting.
- Earthing Problems.
- Power Outages and effect of Auto-Reclose system.
- Load Shedding (Specifically with countries where demand is much higher than generation)
- Power Frequency variations.

And some issues that are indirectly related to Power Quality:

- Reactive Power Compensation issues.
- Load unbalance between the phases and Neutral loading.
- System Resonance – Parallel and Series.
- Maximum Demand control (kVA demand and kW demand).

Once the minimum requirements are defined, with regards to each of these factors, the process for bringing the PQ issues within the benchmarking stated can be worked upon based on various methods that can be adapted.

The process of benchmarking within the given installation requires activities like:

1. Study of installation electrical distribution diagram (SLD – Single line diagram) and identify the critical points on the same where the PQ issues can be measured. i.e. identifying the points for survey.
2. Checking out the specifications of the equipments that are supplied from the specified points in electrical diagram that are selected for survey.
3. After identifying the survey points on electrical installation diagram, defined the different PQ issues that are needed to be surveyed. This should be based upon the equipment specifications too.
4. Check the supply utility standards and incorporate these too at PCC survey point.
5. With identified survey points, one needs to define the survey standards for every PQ issue identified. The survey standard should specify the conditions like:
    - "overall time frame for survey"
    - "time of survey – during specific working shift OR during day or night OR during specific season etc."
    - "monitoring interval time between readings acquired during survey"
    - "number of events for abnormalities captured"
    - "load condition like – maximum or minimum loading"
    - "effect of other loads that are not monitored – if to be kept on or off"
    - "effect of capacitor system for reactive power to be kept on or off or to be checked with both the conditions"
6. Define the right type of measurement and monitoring equipments so as to get the authentic results. The equipment may not be able to monitor all the PQ issues defined in benchmarking. One has to select the right type of equipment so that results obtained are authentic.

The table as shown in the fig.1 can be made so as to get clarity on benchmarking.

Once the table as in Fig.1 is defined, one has to define the PQ issues requirements based upon the electrical installation requirements under consideration.
Fig.2 shows the typical way of defining such benchmarking needs.

After the preparation of such survey requirements (Fig.1) and the benchmarking standards (Fig.2) for the specific requirements, the actual survey work can be commenced.

Once the survey is completed, the survey results needs to be analysed and checked if any of the benchmarking requirements get exceeded. One has to even define up to what extent the benchmarking requirements have been exceeded. The requirement for the PQ improvement equipment's specifications and features has to be based upon the outcome of the benchmarking exercise.

PQ Benchmarking at : XYZ Electrical Installation										
Sr. No.	Survey Point No:	PQ Issues to be surveyed for:	Instrument used	Monitoring Requirements			Load Condition	Other Load Condition	Capacitor Status
				Time frame	Data log interval	Number of events			
1.1	PCC - Transformer Incomer	Voltage Sags & Swells of more than 1min	Krykard ALM-35	24hrs	10 seconds	-Not Applicable-	Maximum and Min Load dring normal 24hrs days work	-Not Applicable-	Capacitor On
1.2		Voltage Outages	On Existing Power Distribution panel - Energy Manager - Rish 12	1 year	-Not Applicable-	Count the events per year	Normal work	-Not Applicable-	Normal status
1.3		Continuous Harmonics	Krykard ALM-35	24hrs	1 min	-Not Applicable-	Maximum Load	-Not Applicable-	With capacitors ON and with capacitors OFF
1.4		Neutral Voltage (Neutral floating)	Krykard ALM-35	24hrs	10 min	-Not Applicable-	Maximum Load	-Not Applicable-	Capacitor On
1.5		Power Values exceeding MD and Reactive Power needs	Krykard ALM-35	24hrs	15 min	Count events within 24 hrs.	Maximum Load	Normal status	Capacitor On
2.1	Load Point -1 on SLD	Continuous Harmonics	Krykard ALM-35	8 hrs shift	1 min	-Not Applicable-	Maximum Load	All other loads ON and All other loads OFF	With capacitors ON and with capacitors OFF
2.2		Voltage Disturbances	Dig Storage Oscilloscope - Tektronics - 6 channel	8 hrs shift	continuous	Capature with single trigger as many as possible.	Maximum Load	All other loads ON and All other loads OFF	With capacitors ON and with capacitors OFF
3.1									

Fig.1.

Sr. No.	Survey Point No:	PQ Issues to be surveyed for:	Requirements
1.1	PCC - Transformer Incomer	Voltage Sags & Swells of more	+10% to -15%
1.2		Voltage Outages	Less than 3 times per year.
1.3		Continuous Harmonics	V-THD% < 2% I-THD% < 8% 3rd Harmonic < 5%
1.4		Neutral Voltage (Neutral floating)	< 1.5 Volts-AC RMS value
1.5		Power Values exceeding MD and Reactive Power needs	MD-KVA < 3200 KVA kVAR < 150 kVAR
2.1	Load Point -1 on SLD	Continuous Harmonics	V-THD% < 3% I-THD% < 12%
2.2		Voltage Disturbances	HF Disturbances frequency > 1kHZ < 650Volts-peak amplitude
3.1			

Fig.2.

Most the PQ improvement equipment suppliers would always influence the requirements and needs. These are based upon the type of equipment specifications they manufacture and need not necessarily match the requirements as defined in the benchmarking process. One has to be careful on such decision making process. The equipments that take care of PQ issue may be inadequate or sometimes over doing the things. Both these has problematic impact. Inadequacy in such equipments can cause the issue to remain unresolved and over compensating may cause the equipment cost to go up and would cause un-necessary financial burden.

Additionally, one even has to look into the aspect if the selected PQ compensating equipment is causing other PQ issue (while the original issue is resolved). The example of this can be seen in further part of this technical paper where "Introduction of Capacitors for Reactive Power Compensation can cause the rise in Harmonics".

Further part of the paper gives the overview on the various equipments used for PQ improvement along with their merits and demerits.

PQ improvement Equipments and their features, usage merits and de-merits:

Let's take a look at the PQ improvement Equipments based upon the PQ issues solving.

Voltage Sags and Swells:

Almost all the installations are worried about this PQ issue. Unless the supply utility power is within the benchmarking needs, one has to look out for taking care of such issues by connecting the appropriate equipments.

The equipments used for taking care of the issue are:

- Solid state voltage stabilizers
- Servo control Voltage stabilizers
- On load Tap Changers for Transformers
- CVT – Constant Voltage Transformers.
- UPS – Uninterrupted Power Supply systems.
- Series boost – buck converter.
- High speed Thyristorised Power Factor Correction (reactive power compensation) system.

Solid State Voltage stabilizers:
Normally uses the semiconductors like thyristors for controlling the voltage.
Even though the voltage (RMS value) is controlled well, normally tends to generate the harmonics on the supply system. Thus, usage of these is in limited low power applications. Specifically, dedicated to single machine.

The fig.3 depicts the typical scheme and the input / output wave-shapes.

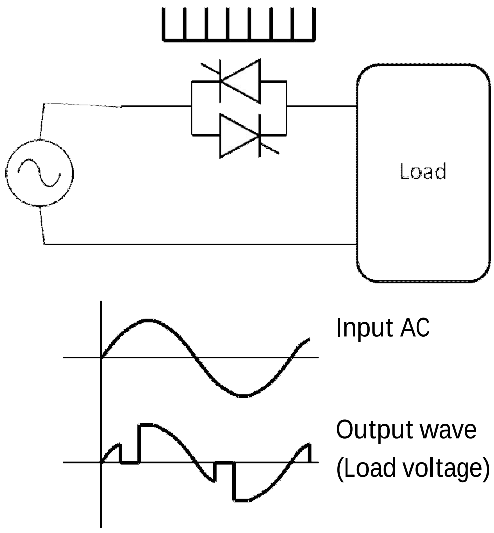


Fig.3.

Servo Control voltage Stabilizers:

Uses the auto transformer with variable voltage that can be controlled by position of the wiper arm. The position of wiper co trols the output voltage. The positioning of the wiper arm is controlled by servo controlled motor.
Sometimes individual phase control servo control too is adapted.

Fig.4 shows the typical scheme used with servo control voltage stabilizer.

The merits of this method are:
- Good voltage regulation.
- Almost no harmonics generated.
- Moderately good efficiency.

The de-merits of this method are:
- Regular maintenance.
- Correction for sudden voltage changes takes few seconds. i.e. no instantaneous correction.
- Limitation on output capacity so usage is restricted to low to medium LT power requirements. (Typical 1kVA to 450kVA).

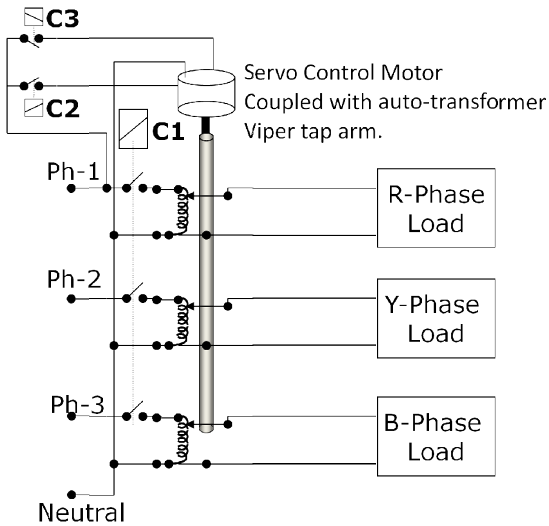
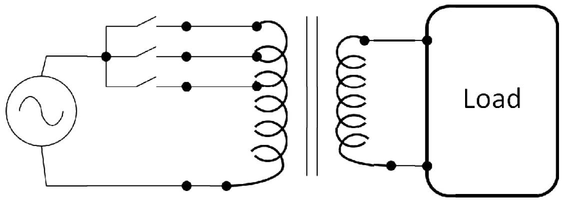


Fig.4.

On Load Tap Changer for Transformers:

The transformer supplying the electrical installation can be fitted with the equipment called "On Load Tap Changer". The various taps of the transformer are selected automatically to control the output voltage regulation. Typical schematic is as in Fig.5.



On Load TAP Changer
Transformer.

Fig.5.

Merits:

- Higher rated capacity control (Normally available up to 10MVA).
- Voltage regulation fairly good (within the difference between the tap voltage ratio).
- Almost no harmonics generated.

De-merits:

- Comparatively high cost of equipment.
- Voltage regulation only against the input supply (utility supply) voltage variations.
- Voltage disturbances (transients) during the tap changing process.
- Regular Maintenance needed.
- Considered by many as "Prone to break-down".

<u>CVT – Constant Voltage Transformers</u>:

Technology uses the effect of magnetic core saturation to maintain the output voltage regulation.

Merits:

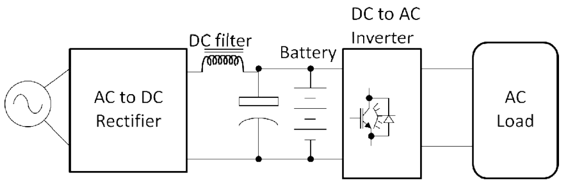
- High speed control over voltage regulation and suitable for fast changing input voltages.
- Voltage regulation with regards to high speed load changes is good.
- No mechanical moving parts thus extremely low maintenance requirements.

De-merits:

- Output voltage waveform is non-sinusoidal creating harmonics issues.
- Transformer efficiency not good (higher core losses)

<u>UPS – Uninterrupted Power Supply</u>:

This technology has wide spread use. It uses the battery stored power and uses power electronics technology to maintain the output voltage regulation.
Typical scheme of UPS is as in Fig.6.



Uninterrupted Power Supply Scheme

Fig.6.

Merits:

- Extremely good output voltage regulation to fast changes in input voltages as well as for fast changes in loads.
- Suitable for other PQ issue like Cycle Loss, Power Outages and Voltage transients etc.
- Normally available with fairly good output sinusoidal waveform.

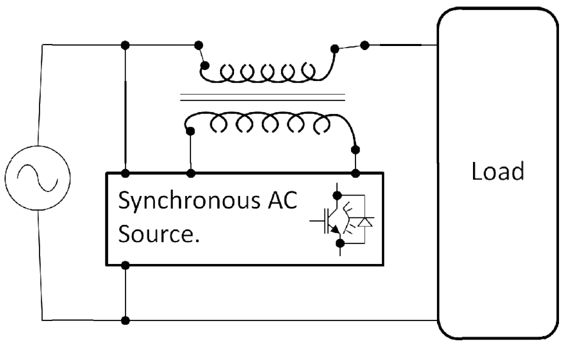
De-merits:

- High cost of equipment.
- Efficiency is not good as compared to other methods.
- Backup battery needs regular maintenance.
- Output surge current handling (load surges) capacity is poor.
- Generates Harmonics on supply system from where it draws the power. (unless special design features to reduce harmonics are incorporated).

<u>Series Boost – Buck Converters</u>:

Technology uses series transformer which is controlled through power electronics based synchronous inverter technology.
Series transformer is connected with the load. The transformer control winding is controlled through the synchronous AC source whose output is controlled with appropriate polarity to increase or decrease the output voltage on high speed basis.

Typical scheme can be as seen in fig.7.



Series Boost Buck Converter Schematic

Fig.7.

Merits:

- Output voltage regulation is extremely good and suitable for fast changing load as well as changes in input voltage.
- Output voltage is without harmonics.
- Additional advantage for utilization against other PQ issues like maintaining limits on Harmonics at PCC and some extent the reactive power control.
- Bi-directional control over voltage regulation. i.e. able to effectively control the sags and swells with single equipment with same efficiency.

De-merits:

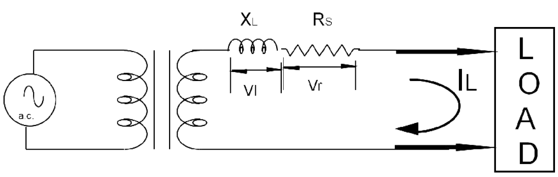
- High cost of equipment.
- Energy efficiency is not good because it has to handle the entire load current in controlling elements.

<u>High Speed Thyristorised Power Factor Correction System</u>:

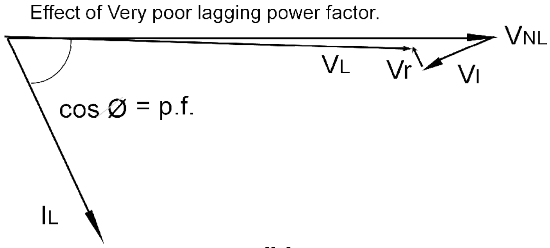
This system is primarily used for reactive power compensation, still has good effect on voltage regulation with regards to load variation.
The technology used is to switch ON/OFF the capacitors and inductors (if needed) using Power Electronic devices like thyristors. The capacitors are controlled based upon the reactive power needs on supply system. Sometimes, even the IGBT based STATCON “Static Condenser” technology is used for reactive power compensation.

By maintaining the power factor near unity almost on instantaneous basis, it gives good voltage regulation against normal inductive source impedance.

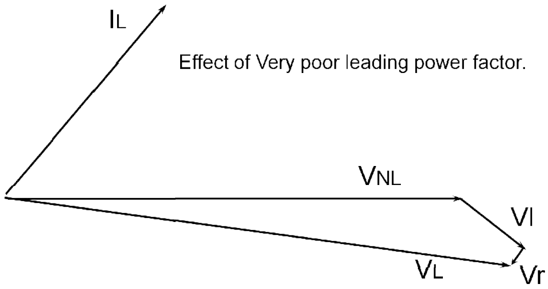
The Phasor representation with regards to Lagging, Leading and Unity Power factor with regards to practical loads like transformer with certain output impedance is depicted as shown in Fig.8 (a). Whereas Fig.8 (b) shows lagging PF phasor representation showing under-voltage with lagging PF. Fig.8 (c) shows over-voltage with leading PF and Fig.8 (d) shows low voltage change with Unity PF.



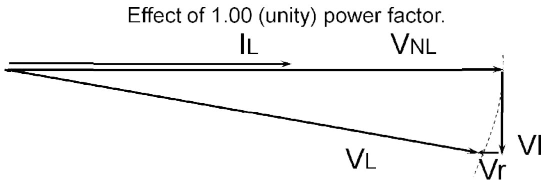
(a)



(b)



(c)



(d)

Fig.8.

The basic schematic of the Dynamic Power Factor Correction System is as shown in the Fig.9.

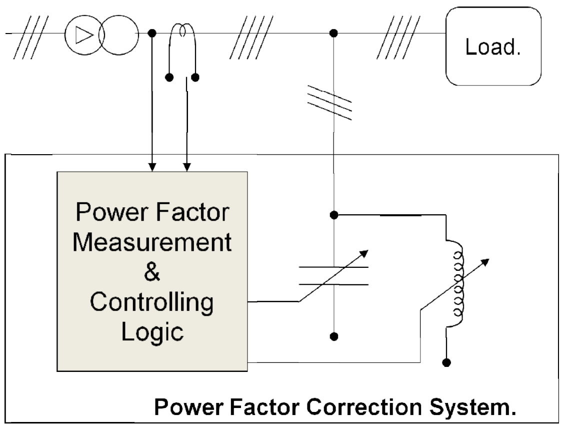


Fig.9.

Merits:

- As the system is used primarily for Reactive power compensation, its usage as voltage regulator is an added benefit.
- Speed of compensation is very fast. Normally within 2 to 5 supply cycles.
- System efficiency is good.
- Almost zero maintenance.

De-merits:

- Cannot compensate for input voltage changes given by utility.
- Such system needs to be adequately protected against harmonics otherwise can give enhancement to harmonics on supply line.

Momentary mains cycles loss:

The momentary mains cycles loss is considered in the range of 0.5 cycles to 30 cycles in the mains voltage.
The mains cycle loss is considered as total loss of voltage during some cycles or reduction in voltage below an acceptable limit for some cycles in mains supply.
Many times it is caused due to starting of high power induction motors.

The loss of cycles for some installations may not be critical and can even be neglected. But in some industries like Semiconductor industries, this is of prime importance. In such industry, loss of cycle can create huge losses to its production and such industries have to be equipped with compensating equipment so as to achieve the "Ride through" effect.

The types of equipments used for providing compensation against this PQ issue are:

- Ferro resonant Transformers.
- UPS – Uninterrupted Power Supply systems.
- Synchronous generators with fly-wheel.

Ferro resonant Transformers:

These are the transformers in category of CVT (constant voltage transformers) but use the effect of saturation energy in conjunction with Capacitors to create the resonance effect.
Normally such kind gives good output voltage regulation effect up to 30% Under voltage cycle losses and for total voltage absent can give the ride through effect for very few cycles (typically up to 5 cycles) after which the voltage amplitude diminishes below acceptable limits.
Typical schematic of Ferro-Resonant transformer schematic is as in Fig.10.

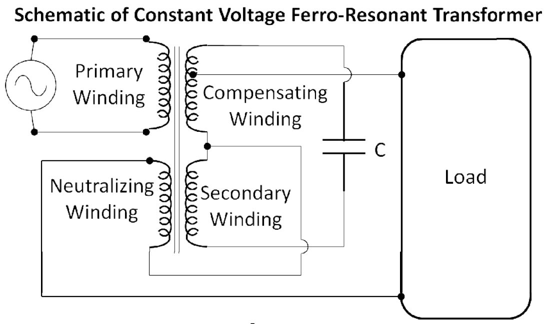


Fig.10.

Merits:

- Effective against cycle loss with amplitude not lesser than 30% of the rated voltage value.
- Harmonic values even though present due to saturation effect are not very high.
- Extremely good voltage regulation effect even against the continuous voltage sags and swells.
- Robust construction without any electromechanical moving parts. Gives good reliability and low maintenance requirements.

De-merits:

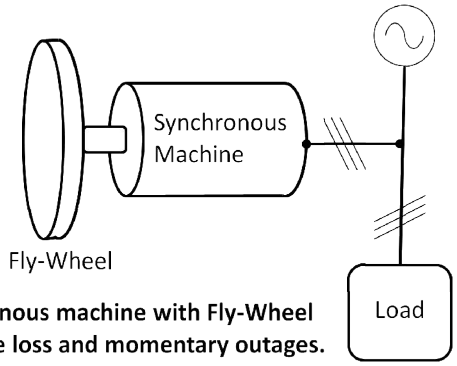
- Usage with lower power ratings. This is because the transformer needs to be operated at much lower loading condition as compared to design of normal transformer of same rating.
- With higher loading than design, the voltage suddenly drops down near zero.
- Due to higher design parameters, the cost is comparatively high.

UPS – Uninterrupted Power Supply:
This equipment is already discussed in previous section of voltage sags and swells. Normally used with primary reason for sustained voltage regulation and thus is very effective with Cycle loss even of longer duration.

Synchronous Generators with Fly-wheel:

As the name suggests, the synchronous machines that are mechanically coupled through a fly-wheel are used. The synchronous machines with normal supply are made to run at synchronous speed in motoring mode. During the cycle loss, the moment of Inertia in flywheel (mechanical energy) continues to run the synchronous machines in a generator mode to go on supplying the electrical system and create a ride through effect.
The dimensions of the fly-wheel and loading conditions determines the time duration of the ride through effect.

Typical scheme is as in Fig.11.



Synchronous machine with Fly-Wheel For cycle loss and momentary outages.

Fig.11.

Merits:

- Effective against the longer duration cycle losses. Well designed system gives the ride through effect up to 30 seconds.
- No harmonics generated.
- During normal motoring operation, synchronous machine with over-excitation can compensate for Reactive Power requirements.
- Good reliability against loading conditions.

De-merits:

- Mechanically moving parts gives rise to human safety and maintenance issues.
- During normal motoring mode, considerable power is lost. Thus, system is considered in-efficient for wastage of power.
- Extremely complex design needing trained manpower for maintenance and rectification issues.

Voltage Surges, Load Current surges and high frequency transients / disturbances:

This topic of Voltage Surges and transient / disturbances is bit complex. There are various categories these phenomena are segregated.
= Short duration high voltage peak transients with high energy content.
= High frequency disturbances riding on sine wave voltages – can be momentary or repetitive.
= Glitches of short duration causing undervoltage spikes or overvoltage spikes of very low energy contents.

These are mainly caused due to
- Lightning strikes.
- Capacitor switching.
- Load switching.
- Short circuit faults.
- High power semiconductor switching with line commutation.
- Switching of SMPS and Converter type loads.

Some of the electricity consuming equipments are capable of handling some type of transients and disturbances. Still one has to take care that such phenomenon are not exceeding the specified values or if some equipments can give undesirable effects for their performance.

The types of equipments for taking care of such PQ problem are:

- Lightning Arresters.
- Usage of Earth conductor over open distribution lines.
- Usage of MOVs (Metal Oxide Varistors) – High Power and normal grade.
- Capacitor filters, Low pass filters like T, L and Pi filters.
- Zero Voltage Capacitor switching and synchronous switching of loads.
- Shielding with differential and common mode disturbance filtering like low impedance power conditioning.

<u>Lightening Arresters:</u>

This equipment is primarily used at the HT side of the Electrical installation. (on primary side of the supply transformer). Sometimes given by supply utility or sometimes used by the consumers themselves. As the name suggests, it’s use is to reduce the amplitude of high energy surges created by lightning strikes. It reduces the extent of the high energy surges by creating low impedance path and bypassing some of the energy content to earthing.

The technology uses MOV blocks encapsulated in polymer housing. The polymer housing is resistant for natural elements like sunlight and humidity (rain water). Earlier technology used porcelain housing. Sometimes resistance graded gap structure too is incorporated.

On transmission lines, the periodically placed Line arresters (Lightning Arresters) are placed to reduce the effect of Lightning Strikes. This can be seen as shown in fig.12.

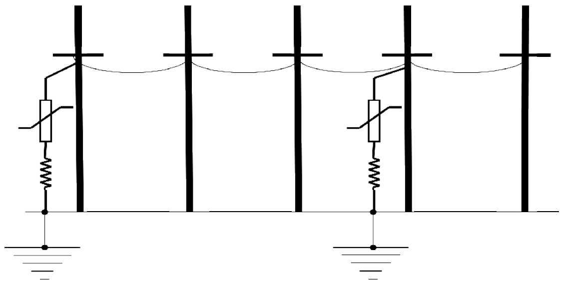


Fig.12.

Merits:
- Effective against the high energy lightning strikes.
- New technology design give a good reliability and almost zero maintenance.

De-merits:
- Does not nullify the entire effect of surges.
- Capable of handling the specified levels of Energy. Beyond which is susceptible for damage.
- Cannot be used for other disturbances that are having amplitude equal or lower than supply voltage.
- Usage is limited only on specified voltage HT feeders.

<u>Usage of Earth Conductor over distribution lines:</u>
Creating the low impedance conductor over the open distribution lines is another effective method against the Lightning strikes.
This method is many times used by supply utility and is used in the area that is Lightning strike prone.

The LT distribution lines are rarely transmitting power in open conductors on overhead poles. Still, with some large size industries, such method is adapted and Earth conductor putting over the higher level of distribution poles is an adapted practice.

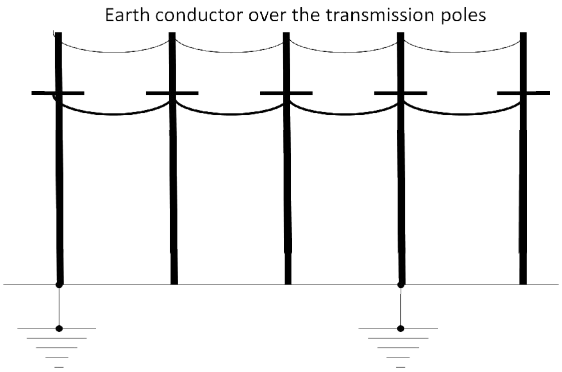


Fig.13.

Fig.13. shows the arrangement of such earth conductors over the transmission poles for Lightning Strikes.

Merits:
- Effective method.
- Prevents the Lightning strike on the power carrying conductors.

De-merits:
- Additional cost of conductor.
- Additional Pole length needed.

Usage of MOV of normal and High energy grade:

The metal oxide varistors uses the non linear characteristic for its conduction. With higher voltage applied, it starts conducting rapidly.
It's like effect of 2 series back to back connected Zener Diodes, but has much higher energy handling capabilities.

Many times, the electricity consuming equipments too use MOVs to handle the higher voltage surges to protect its internal critical circuitry.

Merits:
- Effective against High voltage transients.
- Can handle high frequency surges effectively.
- Effective against intermittent as well as continuous high voltage transients and disturbances (glitches).

De-merits:
- Limitation on Energy handling capacity.
- Selection of right type of MOV needs elaborate study of requirement. i.e. Voltage surge characteristics and maximum energy value to be handled.
- High energy MOVs are costly.

Capacitor Filters and Low Pass filters like T, L and Pi Filters:

The passive elements like Capacitors and Inductors in various configurations are used. They provide the excellent filtering effect against the PQ issues like High frequency voltage disturbances, spikes and even against load generated harmonics.

One has to be careful while designing the appropriate filter configuration against the issues like "voltage regulation against load changes", "Shunt and Series resonance", "Harmonics enhancement" etc.

Merits:
- Strong and Rugged design giving very little maintenance requirements.
- Highly economical.

De-merits:
- Specific design to match the site conditions.
- Any changes in loading conditions on supply lines needs necessary design changes.
- Careful approach while designing the filters which otherwise can give rise to the problems like voltage regulation, resonance and harmonic enhancement.

Zero Voltage Capacitor Switching and Synchronous Switching of Loads:

Switching ON of Capacitors through a conventional electromechanical switch generates high momentary transients on supply system. Thus, many times there is limitation on the biggest size capacitor bank that can be switched on.
The thyristor technology based "Zero differential voltage" switch can give the advantage of almost zero surges as well as able to give a faster switching ON and OFF response time to the capacitor switches.

The various loads like Transformer switch ON and OFF, SMPS switch ON generates the transients on the supply line.
Inductive loads like transformers if made to switch ON during the sine wave peak reduce the transients (momentary DC shift). Synchronous switches using solid state technology in conjunction with electromechanical technology (for conduction loss reduction) is normally used with such issues.

The SMPS switch ON again is like capacitor switching and Zero differential voltage detection switch ON is really effective.

The typical zero differential voltage switch-on scheme of a 3-phase capacitor is as shown in Fig.14 (a) and the switching on waveforms as shown in Fig.14 (b).

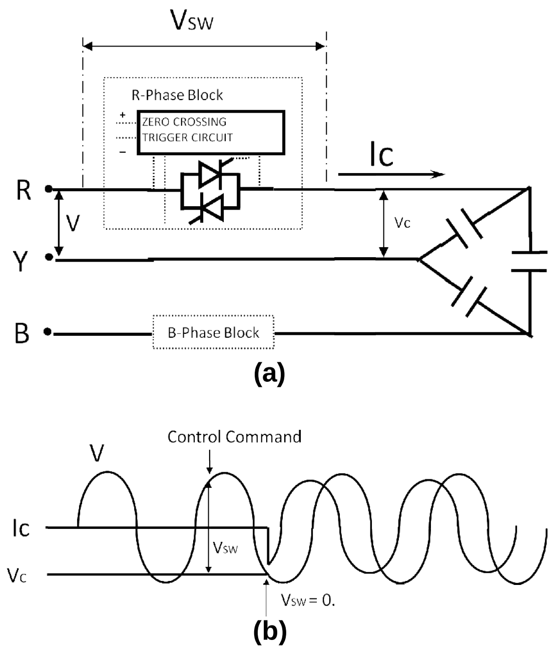


Fig.14.

Merits:

- Zero differential voltage detection switching on of capacitors and SMPS almost eliminates the voltage disturbances on supply system.
- Capacitor switching fast responses can be achieved. – Without waiting for capacitors to be discharged to zero DC voltage before they can be switched ON.
- Well designed system is quite rugged and has reduced maintenance requirements.
- Can be provided with additional protection to the capacitors with the same technology.

De-merits:

- On state conducting watt losses are higher as compared to conventional electromechanical switches.
- Higher costs.

<u>Shielding with differential and common mode disturbance filtering like low impedance power conditioning:</u>

This approach is normally used with low power requirements. This is even incorporated in the electrical equipment design to protect the equipments against the high frequency disturbances.

These type of disturbances are even categorized as EMI (Electro-Magnetic Interference) and are divided into common mode and differential mode disturbances.

Common mode disturbances are the disturbances that are between all the three phases and neutral lines with respect to Earth potential.

Differential mode disturbances are the disturbances that are in between different phases and between phases to neutral.

High frequency common mode and differential mode filters uses high frequency (ferrite core) reactors and capacitors in right configuration.

Merits:

- Simple design and rugged construction.
- Combined common mode and differential mode filters are available easily for the specific applications.
- Low cost.

De-merits:

- Lower power application usage.
- Not suitable for high energy transients.

Current and Voltage Harmonics and Inter-harmonics:

This topic is probably the most widely discussed topic in PQ. Harmonics on supply system is like a cancer and without knowing its presence; it can cause multiple issues with supply related issues like higher energy consumption, maintenance issues, breakdowns in equipments, communication system reliability etc.

Generation of non sinusoidal current loading normally gives rise to voltage harmonics due to the source impedances. Thus, the load that generates such non-sinusoidal currents can generate the harmonic issues for normal linear loads too.

Capacitors used for Power Factor correction absorb the harmonics and can even enhance the levels of harmonics on supply lines.

The recent energy conservation type equipments normally create non-sinusoidal loading on supply system and thus creating harmonics. Some of the examples of the loads that create harmonics on supply lines are:

- Variable speed drives (VFD & DC drives)
- Uninterrupted Power Supplies (UPS)
- SMPS – used with household and control equipments.
- Fluorescent lamps of different types and LED lamps.
- Induction furnaces and Arc furnaces. (even generate inter-harmonics)
- CNC machines and automation servo drives.
- Welding machines.

The non-sinusoidal waveform as per "Fourier Series" mathematical theory are the high frequency sinusoidal components. These high frequency components are further categorized into zero sequence, +ve sequence and –ve sequence components on 3 phase electrical supply system. Such categorization helps in terms of analyzing the nature of problems and the solutions that can be offered.

In general, it's always good to get rid of harmonics on supply system, whatever category it may fit into.

The detailed analysis of harmonics is much lengthier topic, thus this technical paper will not get into those details and proceed with the various solutions available for harmonic mitigation.

The various type of approach and equipments used for Harmonic mitigation are:

- Passive L-C shunt tuned and partially tuned filters
- Low pass filters for 6-pulse converter type systems like AC/DC drives & UPS.
- Usage of 12 pulse converters.
- Z-Winding Transformers for taking care of triplen harmonics.
- Active filters – Static Synchronous Compensators (STATCOM)

Let's take a look at each one on basis of their specific advantages and limitations.

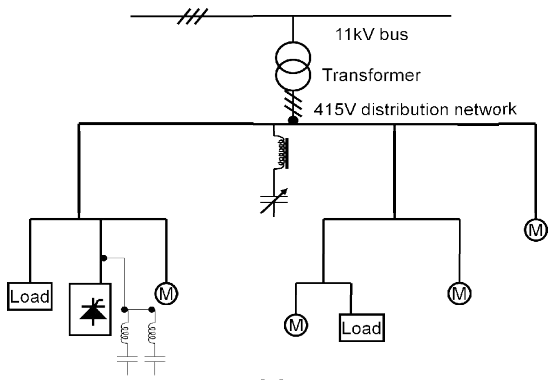
Passive L-C shunt tuned and partially tuned filters:

Probably the oldest approach against harmonic mitigation method. The approach is to filter the individual harmonic number that can be prominent specific to the site condition. The series Inductor and Capacitor (L-C) combination is put in shunt with the supply system. Series L-C combination gives very low impedance at its resonance frequency. Resonance frequency of L-C series circuit is $1 \div (2 \pi \sqrt{LC})$. By this method, the specific harmonic on supply system sees almost zero impedance and gets filtered through the L-C filter.

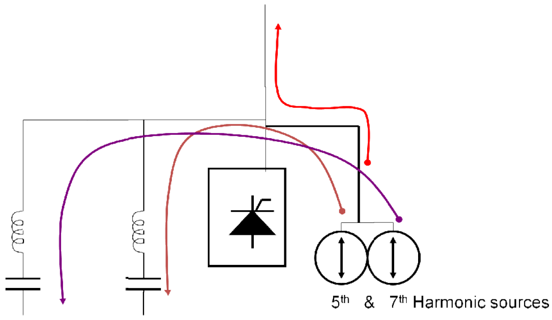
In case of supply system is with wide spectrum of harmonic numbers, for every harmonic number, one has to put a separate L-C filter.

Additionally, such filter is a shunt filter, it cannot see the direction from where the harmonics are generated and takes the approach of general non-directional filter.

The typical LT supply distribution in the industry is shown in Fig.15 (a) and Fig.15 (b) shows the 5th and 7th Harmonic that gets filtered near the harmonic generating load.



(a)



(b)

Fig.15.

One has to be extremely careful while designing of this filter. The design needs to take into account the specific site related impedances of source and loads and various loading conditions. One even has to take the note of reactive power generated by such L-C tuned filters.

Merits:

- Simplified rugged construction by passive electrical components like Reactors and Capacitors.
- Almost zero maintenance.
- Comparative lower cost if system is with one or two harmonic numbers that are prominent.
- Offers additional capacitive reactive power compensation on supply system.

De-merits:

- Site dependent design. Requires complete nodal analysis survey and system impedance calculations for designing.
- Vulnerable to system resonance – specifically with changes in loading conditions.
- Can offer leading PF with low loading conditions and can cause over-voltage issues.
- With wide band spectrum of harmonic numbers present on supply, the cost involvement is high.
- Design is bulky due usage of air core reactors (to avoid saturation effect drift in tuned frequency).

<u>Low pass filters for 6-pulse converter type systems like AC/DC drives & UPS:</u>

A lot of applications in today's industry uses the equipments like AC/DC drives and UPS which uses the full wave rectifiers by usage of power semiconductors. Such rectifiers typically generate prominent 5^{th} and 7^{th} harmonics on supply system. Total Harmonic Distortion on current is typically ranging between 40% to 65%.

The approach of this method is to reduce the current harmonics generated by such applications.

The simplistic approach is to put the series reactors. These approach even though effective to certain extent normally does not bring down the current harmonics to desirable levels. Typical THD% brought down in current harmonics ranges in 25% to 40%.

Better approach is to put the series reactor in combination with shunt L-C tuned filters for 5^{th} and 7^{th} harmonic. Such approach gives far improved results. Typically, the current harmonic THD% comes down to less than 10%. (7.5% to 10% is typical range).

Fig. 16 shows the typical schematic for such Low pass filters.

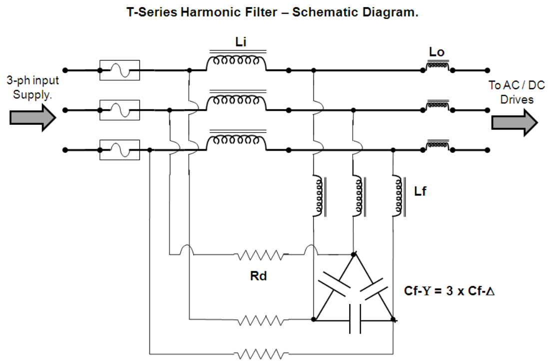


Fig.16.

Merits:

- Extremely effective – gives value for money solution.
- No hassles (normally) of resonance problems.
- Provides some reactive power compensation.
- Rugged construction using passive elements like Inductors, capacitors and resistors.

De-merits:

- Useful only for six pulse converter type of applications.
- Need to put power consuming resistors to avoid overvoltage issues during lower loading conditions.

Usage of 12 pulse converters:

In case of very high power requirements with six pulse converters, this approach is used. It is normally used based upon the application. This approach is used with applications like:

- Induction Furnaces.
- High power AC/DC drives used with Steel rolling mills.

It uses the star and delta windings of the transformer on the secondary. The output of these windings is 60° phase shifted with respect to each other. Thus, overall effect of six pulse converters on the secondary winding is seen by primary winding of transformer as a 12 pulse converter.
The effect of 12 pulse converter is to generate harmonic numbers 11th and 13th. Higher harmonics being higher frequency components can be much easily filtered out and do not travel higher distances on electrical networks.

The typical schematic for 12 pulse converter is as shown in Fig.17.

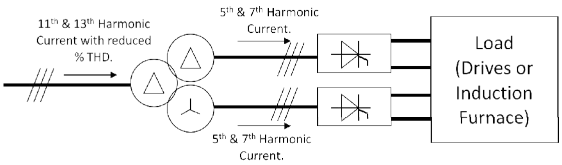


Fig.17.

Merits:

- Extremely effective approach for specific applications.
- Transformer impedance itself acts like added filter for 11th and 13th harmonic generated.
- No need of added series reactors or low pass filters that are used for six pulse converters.

De-merits:

- Needs specially designed transformer with higher K-Factor. (Typical K-Factor is 13)
- Some attention may have to be given to 11th and 13th harmonics on primary of the transformer.
- Product design need to use two numbers of six pulse converters and thus can add up the cost.

Z-winding transformer for taking care of Triplen Harmonics:

Triplen harmonics are 3rd, 9th, 15th,--- etc. These harmonics on 3-phase supply system normally show zero sequence characteristics.

The single phase harmonic prone loads on 3 phase supply system normally create the problems of "Triplen Harmonics".
The effect of triplen harmonics is that they gather together in neutral causing Neutral overloading and Neutral shifting issues.

The tuned filters for taking care of 3rd harmonic are normally very bulky and costly due to the addition of neutral phenomenon.

The better approach is therefore to use Z-winding transformers that effectively cancel out the zero sequence components and reflected current on primary is without such zero sequence components (i.e. without or very little triplen harmonics)

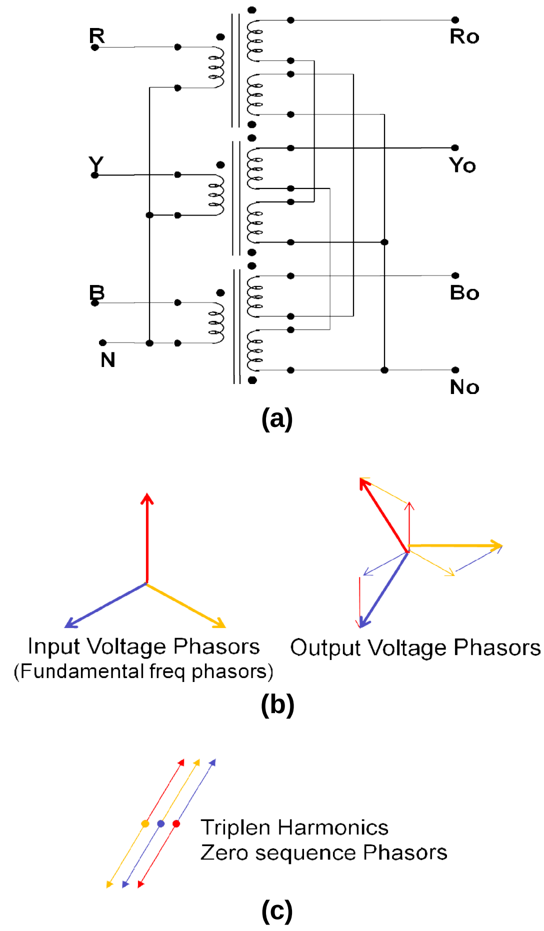


Fig.18.

Schematic of a 3-phase Z-winding transformer is as shown in Fig.18(a) and the phasor relation to input and output for fundamental components are in Fig.18(b). Fig.18(c) shows the zero sequence third harmonic phasors cancelling each other.

Merits:

- Effective value for money solution against “Triplen Harmonics” on 3-phase supply system.
- Energy efficient solution with transformer efficiency of @ 99%.
- Provides effective solution with Neutral floating issue by galvanic isolation of load with triplen harmonics.
- Rugged construction with little maintenance.

De-merits:

- Effective against only zero sequence component harmonics.

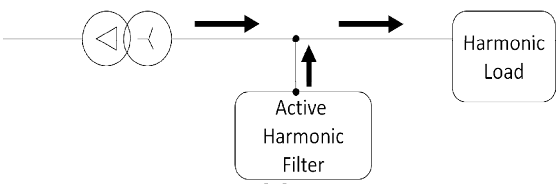
<u>Active Filters – Static Synchronous Compensators (STATCOM):</u>

A recent addition of product in FACTS (Flexible AC Transmission Systems) family. An extremely effective solution for the Harmonic mitigation.

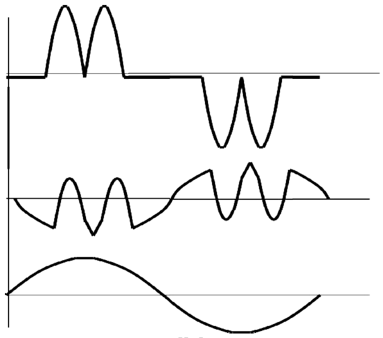
Uses the Power Electronics (IGBT inverters) to counter generate reverse harmonics on supply system. It uses Microprocessor based methods like Digital Signal Processing (DSP) to monitor supply harmonics on line and on real time basis. It then controls the Power Electronics IGBT based inverter to generate the exact reverse harmonics on supply line. This cancels the load generated current harmonics that can be seen at PCC (Point of Common Coupling).

This method has added advantage of able to provide variable reactive power compensation as well as load balancing in three phases.

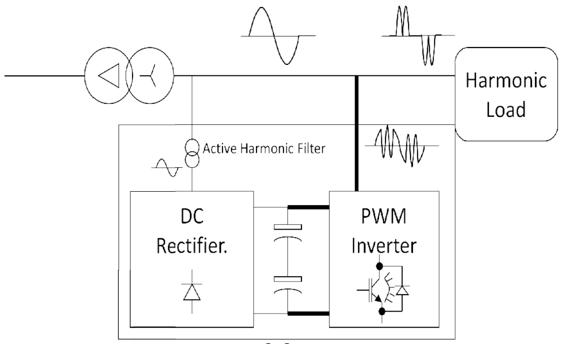
Probably the best known method for harmonic mitigation with present day technology.



(a)



(b)



(c)

Fig.19.

Fig.19(a) shows the positioning of Active Harmonic filter on supply line.

Typical Current wave-shapes as can be seen by Load current, Active Harmonic filter and the supply system transformer are as depicted in Fig.19(b).

Typical schematic of active harmonic filter block diagram is as in Fig.19(c).

Merits:

- Highly suitable for Loads with wide band spectrum of harmonic numbers.
- Bring down THD% factor to much lower level than any other method available with today’s technology. Typically below 5% current THD% factor.
- Added benefit of automatic reactive power compensation and 3-phase load balancing.
- Resistant to system resonance.
- Real time high speed response makes it suitable even for intermittent harmonics.

De-merits:

- Efficiency is not as good as other methods. Typically works between 94% to 97% efficiency.
- Extremely high cost – thus sometimes difficult to justify the economic angles.
- Specialized technology. Thus, needs specialist to take care of any commissioning, maintenance and repair related issues.

Neutral Floating (shifting) and Earthing problems:

There are various type of Neutral Earthing standards used depending upon the country of usage and utility adapted standards.

The LT supply distribution for human safety reasons as well as for connected equipment safety reasons, cannot be left floating with respect to Earth potential.
Neutral therefore is normally earthed at single point (i.e. near supply transformer or generator). Sometimes the earthing is carried out through some impedances. This is normally to limit the level of fault currents against Earth Faults.

There are various reasons for getting the difference between Neutral and Earthing potential.
Major reasons seen are:

- Long length of LT cables from source to load point.
- Excessive Neutral current due to unbalance loading in 3-phases.
- Excessive Neutral current due to load triplen harmonics.
- Increase in resistance of Earth pits. This is many times seasonal and observed during dry seasons where earth resistance is seen higher.
- Earth fault problems in connected equipments.
- Connection problems between Neutral and Earth pit grid points.

There are some specific equipments needed to resolve these issues. Still, the approach is to identify the exact reason for shift in Neutral and Earth potential. Once the reason is known, the solution is normally simple like:

- Improving value of earth resistance (bringing it lower) by water addition or by usage of specialized compounds.
- Reduction in Neutral currents by either reducing phases unbalance or by taking care of triplen harmonics problems.
- Checking the earth fault reason in the connected equipment that has fault and rectifying this.
- Improvement in earth pit grid network on wide spread area if existing earth resistance is at inadequate level.

Some equipments used additionally apart from above mentioned approach for taking care of Neutral Shifting issues are:

- Isolation Transformer.
- Dynamic Load balancing between phases.

<u>Isolation Transformer:</u>

Sometimes, usage of “Isolation Transformer” can help to resolve the issues due to longer cable lengths. With some critical laboratory equipments where there is very critical restrictions between Neutral to Earth protection, usage of Isolation transformer is quite effective.
The neutral earthing on secondary of such isolation transformer which is very close to loads can help reducing the Neutral to Earth potential in such case.

<u>Dynamic Load balancing between phases:</u>

The usage of passive elements like shunt inductors and shunt capacitors across the lines and line to neutral are used for balancing out the loads between the phases.
Where the load is fairly fixed and does not change, the fixed calculated values of reactors and capacitors can suffice to the issue.
But, in case of the loads where unbalance is changing on continuous basis, the dynamic switching of reactors and capacitors is achieved by special “Dynamic load balancing Controller”.

The equipments used for Harmonic filtering like “STATCON” have this specific feature of dynamic load balance. This equipment is capable of generating inductive and capacitive reactive power on supply lines thus can be effectively utilized to generate this additional feature that can be useful.

Power Outages and Effect of Auto-Reclose:

Power outages in third world countries are quite frequent phenomena even though every utility company is trying to improve onto the reliability.
Thus, in such Power Outage prone countries where demand is higher than supply or where the technology up gradation in distribution is needed, normally electrical consumer is always better equipped to take care of such issues.

Unfortunately, in the countries where such phenomenon is rare, power outages creates additional challenge. Here one has to be careful enough to ensure that back-up systems are well maintained and able to give adequate backup arrangement. This is needed to be carried out with regular checkups as the actual utilization of such systems is rare.

Where, the outages are regular phenomena, or in the countries where there is planned outage (Load Shedding) the approach normally is to segregate loads into two or three parts like:

- o Highly Critical loads.
- o Normally Critical loads.
- o Non-Critical loads.

The backup systems in case of outages are then selected based upon the category of criticality.

The critical loads are normally given with on line back up using:

- Uninterrupted Power Supply (UPS)
- Automatic On line Generator set driven through prime-mover like steam turbine, Diesel engine depending upon the availability of fuel of such prime-mover.
- Specifically for Outages that are planned and where electricity cost is on Time dependent basis (TOD metering), a specially designed equipment with backup through stored energy is utilized.
- Making arrangement with utility supply company for alternate emergency feeder and transfer of load through a high speed synchronous switch. (many times solid state switches too are used)
- For auto-reclose effect, the measure such as fly wheel operated synchronous machines is used.

For normally critical loads, the approach is to keep the off line generator set which can be switched ON based upon the requirements or by AMF (auto mains failure) system operated generator set.

The non-critical loads are normally kept off during such outages.

Segregating the loads based upon criticality has the advantage of limiting the capacity of the backup system and reducing additional cost investments.

Let’s just take a little extra look on the electrical supply equipment that has planned outages due to wide gap between demand and supply in those countries.

Planned Outage equipments and TOD metering equipments are mainly segregated into two main categories:

a) Rural Agricultural Supply applications.
b) Urban electrical loads. – Household and small offices / shops.

The category (a):
The rural agricultural area has major loads as Electric pumps. These pumps are driven by standard 3-ph induction motors. Such electrical pump loads contribute to almost 80% of electrical loads in Rural – Agricultural areas.

Thus, distribution companies utilize a special approach to curb down the loading by supply of 3-phases to the specific areas for few hours and balance time giving single phase supply so that there pump motor loads cannot be switched on.
For this purpose, specialized LT load shedding control systems are installed on the LT side of Distribution transformers by utilities.

Such systems in modern day technology comes along with features like:

- Selection of 3-phase supply or 1-phase supply with pre-programmed intervals.
- GSM / GPRS wireless connectivity to control the schedules from remote locations.
- Transformer on line monitoring for better maintenance standards.
- Electricity power monitoring – specifically useful against the thefts of electricity in some countries.

The category (b):

The urban areas, utilities cannot disconnect the power due to shortages. Thus, a separate approach of “Time of Day” (TOD) metering approach is adapted by supply utilities. During the peak demand hours of the day, the

electricity is charged at much higher value than few non critical hours when it is charged at normal rates. Sometimes it is even charged much lower during very low consumption hours like late hours in the night.
Most of the electricity distribution companies in India have 4 steps tariff as per the time criticality.

Under such case, the consumers are advised to connect the specially designed systems.
The features of such specially designed systems are:

- Usage of Battery Storage of Electrical Energy during least tariff hours.
- Utilize the stored energy during peak tariff hours.
- Switching OFF the non-critical loads during peak hours and in applications like water heaters, use low tariff hours for heating.
- Keeps control over critical and non-critical loads depending upon TOD.

Some added features that are convenient from user viewpoints that are added in this like:

- GSM / GPRS control for communicating with user through messaging on mobile phones.
- Pre-set and user set programming schedules.

Power Frequency Variation:

This problem can be more prominent with the supply system with is with smaller localized supply system. Here the effect of high load variation can create the impact on the supply system.

Big size grid utility supply normally does not get affected by the LT consumer loads. Thus, very high variation in Power Frequency is never a major issue and normally it is neglected in most LT installations.

With localized generator supply system, best approach is to improve the generator control system and capacity such that such high frequency variation is not supplied.

Normally, electrical consuming equipments are designed to take care of smaller variations in frequency. And the processes that can get affected with speed changes in the motors connected due to frequency variations are fitted with more accurate method of speed retention like VFDs in close loop speed control.

Some important issues indirectly related to PQ for other Electrical equipments:

The one important issue here is connected with Reactive Power control equipments.

These equipments are fitted on LT distribution to take care of Transmission and Distribution (T & D) losses in current carrying conductors. The consumers normally fit such equipments to avoid Power Factor related penalties and / or to avail financial benefits offered by utility companies against better Power Factor.

Power Factor Controlling equipments:

These are:

- PF improvement capacitors.
- Capacitors Automatic switching (using contactors and high speed switching thyristors)

The capacitors used either fixed or switched for the purpose of Power Factor improvement has an important known bad effect on Harmonics on electrical supply system. As one knows that impedance offered by capacitor on AC system is $X_c = 1 \div (2 \pi f C)$.

The harmonics are high frequency components thus offer low value of Xc capacitive impedance for such higher frequency components. This provides an easy path to the harmonics on Electrical Distribution networks. This most of the times creates enhancement in harmonics on supply lines.

Such effect as can be well understood is bad for the other equipments connected on the same supply lines and even has deteriorating effect on the Capacitors themselves.

Normally, the introduction of line reactors in series with capacitors which has overall effect of resonance frequency that is away from harmonics can take care of the problem.

Such reactors are normally known as "Detuned Reactors" and for the prevalent harmonics, the resonance frequency is adjusted at a value much lower than the harmonic frequencies.

For non-triplen harmonics, the resonance frequency is adjusted at @ 187Hz and 225Hz for 50Hz and 60Hz respectively. Similarly for supply system with triplen harmonics presence, the resonance frequency is adjusted at 134Hz and 160Hz for 50Hz and 60Hz supply systems respectively.

One can even know from such introduction of "Detuned Reactors" that the impedance offered by such L-C combination would give inductive reactance to the harmonics but would be offering capacitive reactive impedance to Fundamental mains frequency of 50Hz or 60Hz.

Typical Impedances seen by L, C and L-C combinations for non-triplen harmonics with 50Hz supply system application of PF correction capacitors can be as shown in Fig.20.

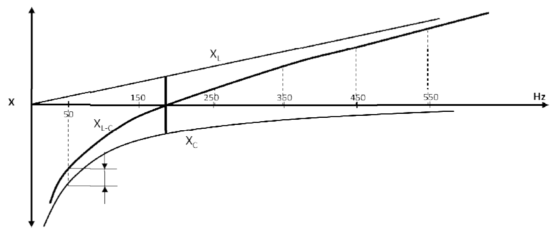


Fig.20.

- **Tushar Mogre.**

(Graduate Engineer – Mumbai University)
(BEE – EM)

Director
TAS PowerTek Pvt. Ltd.
Nasik, India.
(Company specialized in PQ audits and providing PQ solutions).

*****

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