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THE VALUE OF FILTER AND POWER FACTOR COMPENSATION SYSTEMS FOR MINERALS & MINING PLANTS

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Abstract

Due to the large installed electrical power and the large number of electric drives in minerals and mining plants power factor compensation and harmonic filtering has always been an important issue. For the design of harmonic filter and power factor compensation installations several approaches can be taken. The paper describes different concepts and their advantages and analyzes special requirements and design considerations for minerals and mining plants. It also highlights areas where problems can occur and which points need to be addressed carefully. Optimized designs and solutions are discussed in case studies and the resulting energy savings and benefits for the plant operation are shown.

Introduction

In minerals plants a large number of electric drives is used. The high installed electric power makes the operation of electric drives and their power consumption a significant cost factor for plant operation. Thus, efficiency of drive systems, transformer and cable losses, consumption of active and reactive power and harmonics influence operating costs. There are two key aspects that need to be addressed, i.e. power factor and harmonics. The power factor of a drive system or of a plant and its operating power define the consumption of reactive power. With the use of power factor compensation (PFC) systems the amount of reactive power supplied by the utility and the related costs can be reduced or even eliminated. As a result, significant cost savings can be achieved and therefore PFC systems usually are economically attractive. Such PFC systems can be applied in different ways and may use different hardware solutions.

In the past most of the drives were fixed speed applications. Therefore, harmonics and the related problems were less important for operation of a minerals plant and the main focus was on power factor compensation. Due to progress in power electronics frequency converters have become more cost effective. Furthermore, today operating costs are considered stronger and many minerals companies calculate lifecycle cost of new investments. Variable speed drives offer clear advantages at part load conditions and varying operating conditions with varying speed. As a result, variable speed drives have been used more often over the last years. Beside their significant technical and commercial advantages for many applications, variable speed drives produce harmonic disturbances. The higher the percentage of variable speed drives in a minerals plant the more pronounced are potential problems with harmonics. Furthermore, cycloconverter drives most often cannot operate without harmonic filters. The high power of cycloconverter drives used for ball and SAG mills in combination with a rather weak network, which is typical for many large mines, would result in too high harmonic distortions.

Often problems with harmonics are not obvious and may be hidden. If problems exist usually only secondary problems such as over-heating of transformers or disturbances of electronic devices can be seen. Therefore, it is often difficult for operations and maintenance engineers to find the root cause of the problems. Mostly the obvious problems are corrected but the root cause, i.e. the problems with harmonics, remain. As a result, a plant may suffer several malfunctions in different areas over many years without realizing where they come from. Even if there are no problems with an existing plant it is not clear how close to the edge or endangered an installation actually is. Sometimes modifications in the plant or in the boundary conditions can result in problems with harmonics. Typical modifications are the replacement of fixed speed drives by variable speed drives, the expansion of plants, modifications in the plant network, modifications in the power factor compensation equipment and modifications in the supply network.

Beside the increased use of variable speed drives the awareness for harmonic distortions has grown as well. Many plant operators understand that this topic can cause problems for their plant. Severe plant disruption caused by electrically related breakdowns can cost large amounts of money. In addition, electric utilities apply more strict standards and watch for their fulfillment.

Overview of Harmonic Filter and Power Factor Compensation Systems

In the following two important topics are described. The first deals with power factor, active, reactive and apparent power of electric equipment and the influence on the sizing of the equipment as well as on the operating costs of a minerals plant. The second is related to harmonic disturbances, voltage and current distortion and their influence on the equipment and on the operation of a minerals plant. These two items are often interrelated, influence each other and cannot be analyzed independently.

Power Factor

In an AC network the magnitude of the total power (also called apparent power) drawn from the source depends on the nature of the connected loads and their part impedances (resistive and reactive). When the load is purely resistive, current and voltage are in phase. When the load is purely inductive, the current lags behind the voltage by 90°. When the load is purely capacitive, the current leads by 90°. When the load is mixed, the phase angle is determined by the ratio of the resistive and reactive impedances. Transformers, heavily loaded transmission lines, induction motors and under-excited synchronous machines are inductive loads and act as 'sinks' for reactive power resulting in lagging power factor. Shunt capacitors, lightly loaded transmission lines and over-excited synchronous machines are capacitive loads and act as 'sources' for reactive power resulting in a leading power factor. The power factor gives the ratio between active power and apparent power; the vector difference between them is called reactive power. This reactive power is needed to build up electrical and magnetic fields. The most common use is for magnetic fields of motors. Reactive power is normally inductive and most loads need inductive power to function normally. Other than that reactive power adds no useful work and therefore no value. In fact it can become an expensive burden.

In any electrical equipment only the active power serves a useful purpose, whereas the reactive power does not make any useful contribution, but causes additional voltage drops and power losses in the form of heat. Utilization of the installation deteriorates, cables in the network are endangered by the increased load and the voltage relationships become less favorable. A low power factor leads to increased losses and heating of components and to a lower overall system capacity. As a result operating costs of minerals plants increase. Additionally, a low power factor increases costs for utilities too. Drawing reactive power from the power station overloads transmission lines, takes up to 30 % more current and quadratically increases losses. For minerals plants the average power factor at the Point of Common Coupling (PCC) is usually in the range of 0.75 to 0.85 (uncompensated). Therefore utilities normally request their customers to improve the power factor in the range of 0.9 or higher measured at the PCC. If customers do not, they will be penalized and asked to rectify the problem.

Compensating a low power factor can be directly transferred into savings by avoiding:

Paying penalties to the utility

Paying extra losses in cables and transformers due to uncompensated, high load currents

At least sometimes investments in higher rated cables and/or transformers

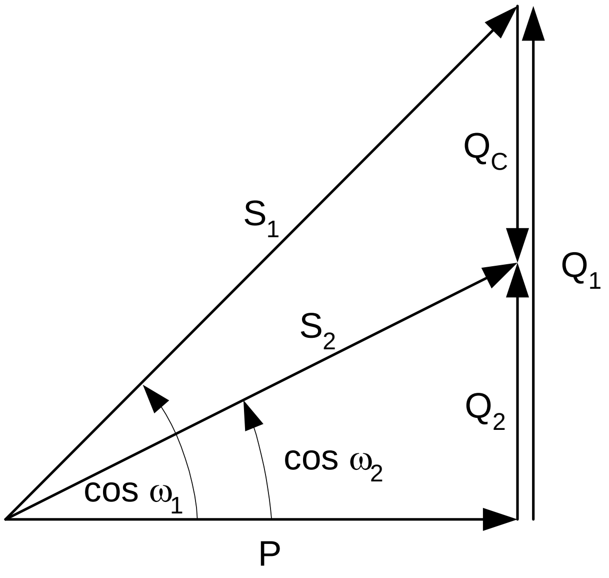

Figure 1. Active power (P), reactive power (Q), apparent power (S) and power factor (cosω); by adding capacitors (Q_c) the power factor is improved (from cosω_1 to cosω_2)

Adding capacitors requires low capital expenditure, low maintenance and no operator actions. Investment in capacitors is therefore easily justified. For excessive reactive power the cost can range from 3 cents to 6 cents or more per kVArh. Actual rates depend on the region and on specific contracts. Maintenance and repair cost are rather low and thus do not influence much the payback analysis.

In a payback analysis different operating conditions can be taken into consideration. Depending on the power factor at part load conditions the energy savings are higher or lower than at rated load. The payback calculation for such compensation systems is rather easy and straightforward. However, in a more detailed calculation model the cost for a civil construction, installation, operation and maintenance as well as for over-sizing of cables and other equipment such as transformers should be considered. In general, power factor compensation usually pays off within rather short time periods (typically much less than a year) and therefore it is practically always done for a minerals plant.

However, power factor compensation cannot be treated independently from harmonic disturbances because these two topics often are interrelated. Hence, harmonics and their impact on the design of filter and compensation systems are explained in the following.

Harmonics

The main sources of harmonics in industrial plants are static power converters (rectifiers and inverters) and arc furnaces. A distorted AC supply signal can be seen as a pure sinusoidal waveform of the fundamental frequency (50 or 60 Hz) with noise or pollution signals imposed. This noise or pollution signals are generally called harmonics. However, there are a real harmonics (signals with frequencies being exactly a multiple of line frequency) and interharmonics (having any frequency in between harmonic frequencies). The voltage or current waveform on a distribution system is actually the sum of 50 or 60Hz sinus and all the harmonics and interharmonics. Increased magnitudes of harmonic/interharmonic currents in a system result in a greater distortion of the waveform and greater problems.

Sources of harmonics can be everywhere. It could be the consumer himself whose non-linear loads such as arc furnace, static converters, etc. generate harmonic current or it could be the utility transporting harmonics from various sources trough its network.

For single phase non-linear loads such as personal computers, printers and fluorescent lamps the generation of third harmonic current is the main concern. For three phase non-linear loads such as variable speed drives, DC drives, welders, etc. the fifth and seventh as well as higher order harmonics are the main concern.

Harmonics can lead to increased line losses, stray losses in the transformers, increased losses of motors and generators, mechanical vibrations and related damages, tripping difficulties, dielectric breakdown, malfunction of electronic equipment, telecommunication problems or metering errors. Further problems are over-heating of equipment resulting in reduced functionality and/or shortened lifetime, tripping of breakers, faulty drive operation, blown fuses or capacitor failures, malfunctioning of protective relays and background noise on telephones due to interference. On top of all of these problems the limits of applicable standards may be exceeded resulting in penalties and costly corrective actions.

The victim could even be a third party, i.e. another consumer in the vicinity, whose power factor compensation capacitors are failing due to harmonics from the neighborhood. Although the capacitors are usually the first ones to suffer under harmonic overload, any other equipment may get trouble due to these imported “foreign” harmonics.

It is obvious that the harmonic pollution has to be controlled, e.g. kept within the limits of recognized standards. There are different ways to achieve this. In order to explain the physical background the Ohm’s law is applied to harmonics.

$$U_n = Z_n \times I_n$$

Where:

U_n is the harmonic voltage at n times line frequency

Z_n is the line impedance at n times line frequency

I_n is the current of a harmonic producing equipment at n times line frequency (n^{th} harmonic)

The simple message from the formula is that the harmonic voltage (e.g. the harmonic pollution) is proportional to the harmonic current that is injected into the network and to the network impedance at this specific harmonic frequency. Thus, it is clear how the harmonic pollution can be reduced. In order to reduce the harmonic voltage U_n either the injection of the harmonic current I_n into the network can be reduced or the network impedance Z_n can be lowered.

Reduction of the Injection of Harmonic Currents

Basically there are two possibilities. The first option is to use equipment with a lower content of harmonics (12-pulse, 24-pulse or even higher pulse number for rectifiers, or “active front end” converters) instead of the commonly used and cheaper 6-pulse equipment. The main disadvantage is the higher price and the more complex circuitry of converters (resulting in a higher vulnerability to disturbances and outages).

The second option is the injection of harmonic currents with the same amplitude as the ones coming from polluting equipment but with opposite phase angle (180 degree shift). In this way so called active filters manage to annihilate a good part of the load harmonics. This works well, especially for harmonics of low order and for stationary running loads where the working point does not change rapidly. On the other hand active filters are still quite expensive, especially for applications at the medium voltage level. Furthermore, their complexity makes them relatively vulnerable to disturbances and outages.

Lowering the Network Impedance

Again there are two possibilities. The first option is to make the network stronger e.g. by installing an additional generator, adding an additional parallel overhead line to the existing one, using an additional or a larger transformer for the supply of harmonic producing loads or by using more parallel cables. By installing additional energy generation and transmission hardware the network impedance usually becomes lower for all frequencies and therefore for all harmonics. But this is a very expensive way for combating harmonics!

The second option is to use (passive) harmonic filters. Such filters consist in minimum of one capacitor and one reactor connected in series. Instead of generally lowering the network impedance for all frequencies, filters do this task very efficiently – for one specific, chosen frequency. This frequency is called tuning frequency of the filter (another name is series resonance frequency). At this specific frequency the filter has an impedance close to zero, building a low impedance path for the harmonic current with the same frequency. So, the first filter can be tuned to the 5th harmonic frequency, the next one to the 7th harmonic, another to the 11th harmonic and so one. Thus, filters have the advantage that they can be specifically designed to the needs. Whatever harmonic causes a problem a filter can be designed just for the frequency of this specific harmonic. Furthermore, harmonic filters are usually the cheapest measure to fight against harmonic pollution. The main disadvantage is that beside the series resonance at the tuning frequency each filter builds with the inductance of the supplying network a so-called parallel resonance. At this specific frequency the impedance of the network and filter system becomes extremely high (theoretically infinite). Recalling Ohm's law, it is clear that this may be a big problem. Even a moderate injection of harmonic current will result in a very high value of the harmonic voltage due to the extreme high $Z_{n.}$ Contrary to the frequency of a series resonance, the frequency of a parallel resonance cannot be fully controlled because it depends only partly on the filter itself (and partly on the network). All in all, problems with parallel resonances are sometimes a challenge even for experienced filter designers, urging him to analyze and treat them with extreme care!

Figure 2 illustrates the phenomenon of a parallel resonance caused by a harmonic filter. The x-axis represents the frequency but given as order of harmonics (1st to 29th). E.g. number 7 means 7 times the line frequency (i.e. 350 Hz or 420 Hz for a 50 Hz or 60 Hz network).

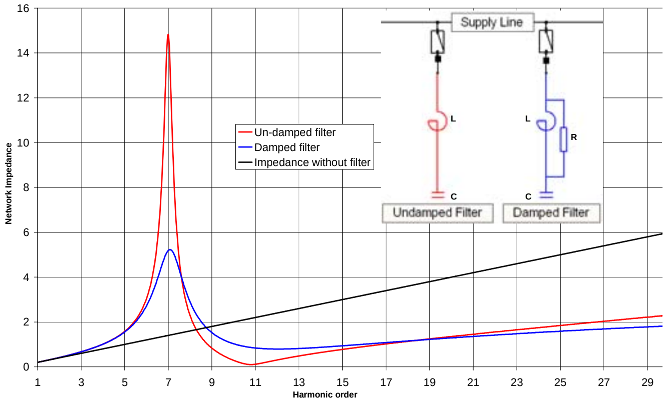

Figure 2. Parallel resonance and the effect of damping of a harmonic filter

Without the filter and without any PFC unit connected to the supply network, the network impedance is linear versus frequency (black line).

The red colored curve shows the impedance of the combination of the supply network and the harmonic filter. Here, the filter is tuned to the 11th harmonic. Such a filter may be found sometimes attached to a large variable speed drive fed by a 12-pulse converter. The reasoning of this filter design is that the lowest harmonic coming from the drive is the 11th and therefore the filtering should start just at this harmonic. This is in fact one of the fundamental rules for filter design but not the only one. As a result, this example for a filter design is not done careful enough or with the necessary experience. The other fundamental principle that is even more important is to take care of parallel resonances! In the figure 10 this rule was not properly considered. The parallel resonance (i.e. the sharp peak of the red curve) appears exactly at the 7th harmonic. Although the 12-pulse fed drive theoretically should not produce any 7th harmonic current, in the real life IT DOES! Even if it would not, other harmonic producing loads within or outside the plant will surely do. As a consequence, there will be high voltage pollution at 350 (420) Hz, and the filter will be overloaded with a huge 7th harmonic current.

The blue colored curve shows the situation where the same filter has been equipped with a damping resistor. It is not meant as a suitable solution for the problem with the parallel resonance for this example. Having parallel resonance at any harmonic frequency is never a good idea. It is much better to keep parallel resonances at a fair distance away from all harmonic frequencies, especially those where strong harmonic currents from non-linear loads have to be expected. Nevertheless, the damping resistor IS a big help for a (careful) filter design. It reduces the magnitude of parallel resonance and therefore considerably lowers the risk of serious troubles (in figure 10 the maximum impedance is lowered about three times, from 15 to 5 Ohm). Furthermore, it lowers the network impedance at higher frequencies and thus helps to additionally reduce ALL harmonics with high order number. In figure 10 it can be seen that the blue curve crosses the red one at about the 19th harmonic order and stays below the red one for all higher orders. Therefore, a damped filter is called "high pass filter" as well.

Beside these advantages, the damping has of course its price. It increases the capital expenditure for the filter and later on creates additional losses that increase the operating costs. However, the cost for the additional losses can be practically reduced to zero by adding another filter element, a so-called auxiliary capacitor. In addition, a damping resistor reduces the effectiveness of the filter to absorb harmonics, especially at the tuning frequency. In figure 10 it can be seen that the blue curve at the 11th harmonic has considerable higher impedance than the red one that almost has zero impedance.

Special Aspects of Filter and Compensation Systems for Minerals Plants

An important difference between minerals plants and the majority of other industrial plants is the area where they are located. Minerals plants are usually built in remote area, far away from the essential energy resources needed to operate the plant.

Typical mining plants have power consumption in the range of 50 to 150 MW. It is often a considerable challenge to deliver such high power with still tolerable deviations from supply quality level achievable for non-remote areas. There are basically two ways to supply a remote plant with electrical energy; to transport it through (long) overhead lines from the public supply system or to generate it locally by proprietary generators (island network). Each of them has its own specific disadvantages.

Public Network Feeding the Plant through a Long Overhead Line

The long line between the generator station and the plant introduces a number of problems at the plant site.

The first is the limitation of short circuit power that is available at the plant site caused by the overhead line. Short circuit power is one of most important features for an electrical supply system. Generally it can be stated the higher – the better. Unfortunately the line itself heavily limits the achievable short circuit power at its end. The following table shows the situation where at the beginning of the line indefinitely strong / large generators supply the network.

Table 1. Theoretical short circuit power at a plant

Nominal voltage of the trans-mission line	Maximum theoretically achievable short circuit power at the end (plant side) of a typical 3x1 conductor overhead line			
	Length of overhead line			
	100 km	200 km	300 km	400 km
132 kV	540 MVA	270 MVA	180 MVA	135 MVA
230 kV	1620 MVA	810 MVA	540 MVA	405 MVA

It is obvious that even the strongest network at the begin of the line cannot assure high levels of short circuit power at the end of the line. On the other hand, it is clear that increasing the line voltage is very advantageous (but not always feasible!).

At the medium voltage level, at which the plant loads operate, the values for short circuit power are even lower due to the impedance of HV/MV transformer. The consequences of (extremely) low short circuit power at plant site are:

voltage stability is poor (small changes in plant loading cause big changes in the supply voltage)

harmonic voltage distortions are high

commutation notches are deep

commutation of big converters may become too slow or even impossible

flicker may become high

the control of variable speed drives may become instable

the parallel resonance between the network impedance and the PFC system may appear at a frequency critically close to the line frequency, which in turn may make the whole electrical system instable causing a full blackout

other parallel resonances may come critically close to the third and/or second harmonic frequency, which poses a high risk during transient conditions (energizing of large transformers and/or fixed speed drives)

The second problem is the vulnerability of long overhead lines that are generally more vulnerable to a number of external factors than power transmission by cables. For the minerals industry the overhead lines are especially a high risk due to:

length of the line (usually some hundred kilometers)

the often very rough environment (earthquake areas, mountains, trees, birds, lightning, extreme atmospheric conditions, etc.)

As a consequence of such a high exposure to different external influences, overhead lines deliver voltage with frequent dips, swells and even single-phase or three-phase interruptions. Of course, neither of them is beneficial for the plant production.

The third problem is that overhead lines inherently cause parallel resonances. Overhead lines cause a (theoretically indefinite) number of parallel resonances. The longer the line, the lower the frequency of the first parallel resonance and the lower the frequency between the other resonances at higher frequencies. We could say that the DENSITY, i.e. the number of parallel resonances per frequency unit, increases with the length of the line.

In practical terms, long overhead lines cause a number of parallel resonances in the low frequency area (100 to 3000 Hz) where energy-rich harmonics are produced and where the national and international standards define limits for harmonic distortion. Making the operation of the plant safe and fulfilling the standards becomes increasingly difficult with increasing length of the overhead line.

Local Generator Station Feeding the Plant (Island Network)

Beside the investment cost and the necessity to transport the energy media (coal, oil or gas) to the site, there is only one considerable electrical disadvantage of this solution, i.e. the relatively instable line frequency.

Due to limited generation capacity, all sudden changes in the plant loading result in transient changes of the line frequency (50 or 60 Hz). The same happens in case when one of the generators suddenly trips. The frequency changes are then much higher (5 % and more) than what is to be expected in strong interconnected public networks. However, for minerals plants this frequency instability of the island network is actually not considerably different to the frequency instability in the typical public networks supplying remote plants. Due to the fact that most of minerals plants are in the countries or areas where the network is rather weak and the "hot" spare generating capacity (one or more generators running unloaded or only partly loaded in order to provide spare capacity in case of a sudden load increase) is often not kept.

The disadvantages mentioned in the case of a supply from a public network through long lines are for island networks either not present or the magnitude of possible problems is much lower.

Gearless Mill Drives

In contrary to many other industrial plants, mineral plants with cycloconverter drives most often cannot operate without harmonic filters. The high power of cycloconverter drives used for ball and SAG mills in combination with rather weak networks would result in too high harmonic distortions. Therefore, the availability of the power factor compensation and harmonic filter systems for such plants is of high importance. In order to achieve this, the power factor compensation and harmonic filter system is usually designed rather conservative (i.e. robust) and at least partly redundant.

Filter 2 and filter 3 often are needed in order to keep away parallel resonances from second and/or third harmonic. Such resonances would lead to potentially disastrous consequences. Although these filter units are not contributing much to the filtering itself, they can be realized only with relatively high capacitive power due to their narrow area of frequencies where they considerably lower the network impedance. Sometimes they need so much power that the remaining power (for the filters with higher tuning frequencies) is not sufficient to fulfill the target for harmonic distortions. In such cases the total capacitive power goes beyond the power which would be otherwise sufficient for achieving the required power factor.

Implication for Filter Design

Resonances due to long lines are not controllable. The longer the line, the higher is the number of parallel resonances in the low frequency area (where the limits for harmonic distortions apply). This results sometimes in a relatively high number of tuned filters because the problems are hard to solve only with damping. It is especially critical in case of applying IEEE standard (limits for current export).

The line frequency is often relatively unstable (variations of 5 % and more). This requires a careful design of the filter requiring well damped filters and considerable kVAr power for each filter units, especially for those with lower tuning frequencies.

Interharmonics are not nearly that precisely defined and limited in the major standards as "real" harmonics. The trend is to limit them to the level of neighboring even harmonics. These cause the same trouble as "real" harmonics with only one known exception, i.e. they can disturb the ripple control systems (which are more and more getting irrelevant due to other, more sophisticated and cheaper communication and control solutions).

Interharmonics and parallel resonances (in special cases flicker with first child above line frequency or even harmonics with second children) have an additional impact on the design. Frequency variable interharmonics make it necessary to use damped filters.

Further Considerations

The basis is always a passive PFC and harmonic filter system that consists only of harmonic filters built from passive components (reactors, capacitors and resistors). When the basic system cannot fulfill all requirements, active add-ons have to be considered. These can be static type systems based on semiconductors (thyristor, IGBT, IGCT) or rotating type systems based on synchronous motors running at no load acting as a source of variable reactive power.

Passive PFC and harmonic filter systems are the most commonly used type. These are relatively cheap and reliable. It can help for harmonic distortions where the filters are very effective. They are very effective in improving the power factor (although not step-less). They are effective in reducing the steepness of the commutation notch shape, in reducing the notch-area and in reducing the overshooting at the beginning and the end of every notch (caused by resonances at higher frequencies). They are very helpful for the commutation of converters by lowering the effective network impedances (especially for higher frequencies) seen from the converter. Finally, they are very effective in shifting parallel resonances occurring at 2nd or 3rd harmonic frequency into non-critical frequency areas.

Active rotating add-ons for the PFC and harmonic filter systems are the oldest type of all. These are basically synchronous motors running at no load. They produce almost pure reactive power, capacitive or inductive depending on the applied excitation. This way they can generate any amount of reactive power (step-less, within the design limits). Therefore, they are often used for power factor control, but mostly only as a nice “side effect”. The primary incentive to introduce such an expensive machine is usually to lower the network impedance, i.e. to increase the network short circuit power, with all its benefits for the plant operation. On the other hand, as mentioned, they are not cheap and require maintenance.

SVC (Static Var Controller) active add-ons for the PFC and harmonic filter systems are the older (and cheaper!) type of the static add-ons. It can do a lot in improving the power quality for minerals and mining plants. It consists basically of one passive component (mostly a reactor) that is switched / controlled by thyristors in order to provide step-less control of reactive power. Often one set of passive harmonic filters is added as well which reduces harmonic distortions caused by thyristor controlled components themselves (and by other harmonic sources connected to the same electrical point). It is primarily used for voltage stabilization (symmetrical and, if needed, asymmetrical, for each phase separately). It can stabilize as well the power and voltage oscillations typical for very weak networks. In combination with a set of passive harmonic filters it can provide all benefits typical for passive PFC and harmonic filter systems (as described above).

Technologically newer active static add-ons are using faster switching semiconductors and, in contrast to SVCs with thyristors, intermediate energy storing (either in large capacitors or in superconducting reactors). So, depending on their design, they can do almost everything, at least for a short time. They can control voltage, reactive and active power, phase symmetry, and they can further filter away voltage and current distortions (harmonics and interharmonics) without causing parallel resonances, stabilize weak networks and reduce flicker. Such high functionality has, of course, its cost. These devices are still quite expensive and their effective help is strictly related to the design power, especially the amount of internally stored energy.

Design of Power Factor Compensation and Harmonic Filtering Systems

Basically the filter functionality can be realized either by active or passive filters.

Active filtering can provide efficient technical solutions, particularly in the low or very low frequency range. It is also effective for sub-harmonics or interharmonics. The main advantage of an active filter is that it is auto-adaptive to the frequencies that should be filtered out. Therefore, unlike passive filters that are tuned to particular frequencies, active filters can be considered as broadband filters. However, their price is still very high compared to other solutions and due to this big disadvantage they are practically inexistent in industrial plants.

Passive filtering requires particular attention to the emission spectrum of the loads. This is especially true when interharmonics are present as well. The risk of exciting parallel resonances is a real concern and therefore passive filters in general should be damped. Usually large power installations require a careful and complete investigation to define the filtering system. Moreover, passive filters cannot be operated independently of each other or independently of other reactive power compensation systems. Therefore the complete installation should be considered in the analysis and design of passive filter systems.

General Design Aspects

In general, the capacitive power needed to improve the power factor tends to decrease due to the increased use of variable speed drives that already have an excellent power factor.

During the design process it is necessary to bundle the available resources in order to utilize them most efficiently. With “resources” primarily “capacitive power” is meant. The effectiveness of harmonic filtering greatly depends on the capacitive power that is installed in the harmonic filters. Thus, the combination of increased use of harmonic producing loads and their generally high power factor makes it more and more difficult to find good solutions for a suitable power factor compensation and harmonic filtering system.

As a consequence, the available capacitive power has to be installed in a minimal number of harmonic filters that guarantees the fulfillment of all requirements. Moreover, the filter number is a major cost factor and the effectiveness, safety and reliability of filters generally increase with their power.

The next question is where the harmonic filters should be connected. In most cases the choice is the main medium voltage bus in the plant. This is the electrical point where the best utilization of the given harmonic filter resources is possible.

The consequence of the above-mentioned factors is that in most cases a central compensation at the medium voltage level is the optimum solution. Only in very specific cases it may be justified to put additional filters on LV busbars and/or MV busbars that have a different voltage level than the busbar where the central compensation is connected. Mostly, this is the case where a central compensation cannot assure compliance with the limits for harmonic pollution throughout the whole electrical network of the plant with reasonable technical measures and at thus at reasonable cost.

Design and Optimization Process

The design of a power factor compensation and harmonic filtering system requires information about the power system and the environment in which the PFC system will be installed. Beside the electrical characteristics such as the nominal system line-to-line voltage and the fundamental frequency, environmental data such as ambient temperature, wind loading, site altitude, seismic zone of the site, air pollution, etc. should be available. The owner should make decisions such as the location of a PFC system (indoor or outdoor) and operating constraints before the design of a PFC system starts, because these decisions will affect certain design aspects. A clear understanding of the plant duty cycle and possible network variations within the plant (changes in the supply paths influenced by tie-breakers, links, the number of transformers in operation, etc.) are also important input for the design.

Based on the total amount of capacitive power needed and on the harmonic generation, an initial estimate of the number, size and tuning of the filters is made. The tuning usually is chosen such that harmonic voltage and current distortion are kept within the limits of the specified harmonic performance criteria. To meet this objective the filter typically is tuned to the lowest frequency of the most significant harmonics. For example, if the 5th and 7th harmonics are the highest harmonic current levels, a single filter tuned close to the 5th harmonic may be sufficient to limit the distortion. However, later evaluations may show that additional filters tuned for higher harmonics – and sometimes for lower harmonics too – may be required.

In most cases the filter(s) must limit the voltage distortions, in some cases the current distortions too. This has to be guaranteed across a range of normal system configurations as well as for a number of defined abnormal (exceptional) conditions.

Significant experience is required to search and find the most critical cases primarily with respect to filter performance but to meet a number of other criteria as well. Otherwise it would be necessary to evaluate a large number of operating conditions (hundreds and even thousands) that result from the variation of all factors that influence the operational behavior. Each critical case may impact the filter design and result in a change of the concept for the PFC and harmonic filtering system. E.g. a filter design may work fine for almost all cases but not for certain exceptional circumstances. If crucial cases are overlooked in the evaluation and the filter design, catastrophic failures may occur later on.

In practice some iterations are necessary until the optimized concept is established. A number of factors should be considered when performing these studies. The importance of these factors may vary for different installations but the following list provides a good overview of topics that need to be considered.

Number of filters, their tuning and damping
Control and switching concept for single filters or filter groups
Outage of a filter bank, if more than one bank is used
Voltage change caused by switching of filter(s)
System voltage variation
Load variation
Power system configurations (normal and contingency)
Capacitors(s) and/or harmonic filter(s) in the electrical neighborhood of the PCC
Detuning of a bank by changes in the system frequency, manufacturing tolerances of components and variation of the capacitance with severe temperatures
Characteristic and non-characteristic harmonics
System background harmonics
Possibilities to build filters from identical components (mostly identical C-cans and/or R-elements for all or a number of filters)

At the end of this iterative process the final data are obtained such as the number of filters, filter tuning, impedance values for filter components and the connection point of the filters based on the compliance with the prescribed harmonic standard or specific customer requirements.

Component Ratings

As soon as the filter harmonic performance is optimized, the filter component ratings have to be determined. In this design stage it still may be necessary to perform more iterations in order to refine the chosen concept. This is important if some components are excessively loaded and therefore the design would be unnecessarily expensive.

Generally, it is recommended to conservatively determine the component ratings and to design the components for the worst foreseeable loading case including a reasonable safety margin. Only then the customer can really expect a high reliability and a lifetime of the harmonic filters of 20 to 25 years.

Protection Concept

Filters consist of three main components, i.e. reactors, capacitors and resistors. Ideally all of them are protected by specific protection equipment. However, due to the loading currents with the combination of frequency components, total protection would require specific and at least partly very sophisticated hardware and software. Therefore, the optimum between sophisticated protection schemes and the safety and reliability resulting from properly and conservatively designed components has to be found for each specific application.

Control and Switching Concept

The control of filter and compensation systems can be done in various ways from very simple to rather sophisticated depending on the needs of an installation. The equipment can be controlled manually. This is only appropriate for very stable and constant load characteristics. There can be a fixed connection between the load that should be compensated and the compensation unit. This means that both load and compensation unit are switched on and off together. This is a rather simple way of control, however only feasible for a limited number of applications e.g. single compensation of a motor. For more complex compensation systems the control is usually automated. A controller is used to automatically switch on or off single units (filters or capacitors) or unit groups. Most often a dedicated power factor controller is used to keep the power factor constant, either of the entire plant or of parts of the plant e.g. certain groups of loads such as all loads at a specific MV bus. The control can also be realized with a PLC that uses the target power factor as control variable or even more sophisticated control algorithms with additional decision criteria and control variables.

Switching the filters ON and OFF has to follow a simple but strict rule: the first filter to be connected is the one with the lowest tuning frequency, followed by the one with next higher tuning frequency and so on until finally the filter with the highest tuning frequency is connected. Disconnecting has to be started with the filter that has the highest tuning frequency and ends with the one that has the lowest tuning frequency.

Problems, Solutions and Case Studies

Problems *(Table 2)* with Harmonics

Electrical energy is a very specific good because the user affects its quality more than the producer or supplier. Therefore, both supplier and user are partners in maintaining the quality of the electrical supply. Harmonics are a major factor that influences this quality. Today's minerals plants use more and more equipment that produces harmonics and therefore the electrical disturbance by harmonics is increasing as well.

Table 2. Symptoms of problems with harmonics for electrical equipment

Transformers	There is a higher temperature rise in the windings even though the transformer is apparently not fully loaded. Additional heating comes from both, current and voltage harmonics. Accelerated aging and/or de-rated operation could result. There is a noticeable change in the audible noise.
Cables	There is regular over-heating even though the loading is apparently adequate. This leads to accelerated aging and/or de-rated operation.
Motors	There is regular over-heating even though the loading is apparently adequate. Torque oscillations occur in the rotor leading to accelerated aging and/or fatigue, especially where mechanical resonances exist. The torque may be reduced as well. The motor may refuse to start smoothly (cogging) or may run with very high slip (crawling). There is a noticeable change in the audible noise of the machine.
Capacitors	The shape is expanding as a result of increased heating and voltage stress. At the end the dielectric breaks down and the capacitor explodes. Apart from damaging the equipment this presents a danger to the personnel.
Compensation units	The units switch off inadvertently. This is a very good indication of a harmonic problem. They fail individually at varying times.
PLC and DCS systems	Start / stop sequence and other functions become erratic for no apparent reason.
Computers	There are malfunctions including loss of data.
Circuit breakers	Once tripped circuit breakers tend to re-strike. This can damage both circuit breaker and load.
Electronic devices	Display problems occur with cathode ray displays (TVs, PCs, etc.). Equipment and instruments perform erratic and unpredictably with malfunctions which sometimes can be subtle. Power electronic systems fire incorrectly and are eventually destroyed.
Measuring instruments	Older designs with electromagnetic counters can suffer errors of up to 20 % for active power and 35 % for apparent power. Power meters can be severely affected by harmonics.

The biggest worry however is that many operations and maintenance engineers are not aware of potential or existing problems in the first place. Recognizing that a harmonics related problem exists is a big step forward to prevent significant long-term damage in a plant and to save the related costs. If any of the symptoms listed below are experienced there is a high probability that problems with harmonics exist.

Quite often situations as described above are accepted as an inconvenience to be endured. Protection levels are raised even if the equipment may not be any more properly protected. Equipment that is over-heating is cooled by additional fans or is replaced by larger sized (over-sized) devices. Failed parts or components are replaced even if the problems occur more than once. Neither of these actions will address the root cause of the problems. It is often uneconomic and will not cure the problems.

If any of these problems are experienced a harmonics problem likely exists. The plant could age more than expected. Harmonics act as an aging accelerator and can rapidly destroy components or even parts of a plant. It is important to take positive action and to cure the source of the harmonics problem. Expert advice and experience is usually very helpful to make progress, identify the root causes of the problems and to find measures to overcome them.

Case Studies (Tables 3, 4 and 5)

In the following, examples of harmonic filter installations for large mines in South America and Australia are shown. Beside the key data of the plant special requirements and critical issues are briefly explained. These case studies give an overview of design considerations of such installations.

Table 3. Main data of Antamina plant (Peru)

Network	Public
Site altitude	4300 m.a.s.l.
High voltage	220 kV
Number of overhead lines Length	2 200 and 230 km
Number of main HV/MV transformers	2
Medium voltage for GMDs and filters	23 kV
Minimum short circuit at medium voltage	165 MVA
Line frequency / frequency variation for steady state condition	60Hz ± 3 %
Maximum plant demand	Approx. 150 MVA
Number of GMDs Rated power of each GMD Number of pulses for rectifier	4 1x20 & 3x11 MW 12
Number of filter sets Rated power per set	2 35 MVAr
Number of filters in one filter set Tuned for harmonic order	7 2,3,4,5,7,11,13
Target value for power factor at 220 kV	0.95
Harmonic distortions to be limited according to (applicable standard)	IEEE 519

At the Antamina plant (Fig. 3) (Peru) the main specific issues were the long HV overhead lines, resulting in extremely low short circuit power at mine site and the instability of line frequency during transient conditions (up to 5 %).

In addition the following active add-ons have been installed:

- 2 x 15 MVA synchronous condensers at the 23 kV main plant busbars
- 1 x SVC (Static VAR Controller) consisting of 3 harmonic filters (5, 7, 11) with a total of 81.5MVAr and a TCR (Thyristor Controlled Reactor) with 135 MVAr, installed on 220 kV line, about 50km away from the plant

Both active add-ons, the SVC and the synchronous condensers were necessary in order to make plant operation at all possible. The SVC has primarily the function to stabilize the voltage, and the synchronous condensers are used to rise the short circuit power at the 23kV busbars.

At Telfer (Australia) the island network has sufficient short circuit power, which made possible to design a relatively simple and cost effective filter system. However, the inherent instability of the line frequency for island systems has raised some design questions such as whether to allow operating limitations for the harmonic filter system when the frequency variation goes beyond certain level or to invest into two additional filters tuned for the second harmonic (100 Hz) and to increase the kVAr power in the already proposed filters.


Figure 3. Filter installation at Antamina

The agreed solution was not to invest into more or larger filters, but to restrict usage of filters such that for line frequencies lower than 48.5 Hz or higher than 52.5 Hz only one of two filter sets can be operated. For line frequencies lower than 47.5 Hz or higher than 55 Hz no filter set is allowed to be operated.

Table 4. Main data of Telfer plant (Australia)

Network	Island, 3x57 MVA generators
Site altitude	500 m.a.s.l.
High voltage	–
Medium voltage for GMDs and filters	33 kV
Minimum short circuit at medium voltage	345 MVA
Line frequency / frequency variation for steady state condition	50Hz ± 0.5 %
Maximum plant demand	Approx. 100 MVA
Number of GMDs Rated power of each GMD Number of pulses for rectifier	2 15 MW 12
Number of filter sets Rated power per set	2 13.5 MVAr
Number of filters in one filter set Tuned for harmonic order	4 3, 4, 5, 7
Target value for power factor at 33 kV	0.85 – 0.90
Harmonic distortions to be limited according to (applicable standard)	IEC 61000-3-6 / Class 2

Specific issues for the Collahuasi plant (Chile) were long HV overhead lines resulting in low short circuit power at mine site and instability of the line frequency during transient conditions. In addition, a number of old, existing harmonic filters had to be integrated (and further used with the new harmonic filters). Finally, both, power factor and harmonic distortion requirements still had to be fulfilled with only two of three main filter sets operating. This resulted in a rather sophisticated control system covering power factor control and handling of switching sequences for all possible operating conditions and modes.

Recommendations for Modifications of Existing Plants

Modifications of existing plants can be caused by modifying or adding loads or by changes in the supply network. Adding loads definitively influences the plant power factor. Some types of load such as variable speed drives, heating devices, synchronous motors and capacitors will rather improve the power factor whereas others such as small and/or lightly loaded induction motors, arc furnaces, fluorescent lighting, sub-synchronous cascades, cycloconverters and DC drives rather worsen it.

Table 5. Main data of Collahuasi plant (Chile)

Network	Public
Site altitude	4400 m.a.s.l.
High voltage	220 kV
Number of overhead lines Length	2 300 and 200 km
Number of main HV/MV transformers	3
Medium voltage for GMDs and filters	23 kV
Minimum short circuit at medium voltage	250 MVA
Line frequency / frequency variation for steady state condition	50Hz ± 0.5 %
Maximum plant demand	Approx. 200 MVA
Number of GMDs Rated power of each GMD Number of pulses for rectifier	3 1x21 & 2x15.5 MW 12
Number of filter sets Rated power per set	3 35 MVAr
Number of filters in one filter set Tuned for harmonic order	5 2, 3, 5, 7, 11
Number of auxiliary filter sets Rated power per set	1 20 MVAr
Number of filters in one filter set Tuned for harmonic order	4 2, 3, 5, 7
Target value for power factor at 220 kV	0.95
Harmonic distortions to be limited according to (applicable standard)	IEEE 519

If loads that produce harmonics are added, the distortions within the plant network definitely are influenced and generally speaking increased.

In addition, adding loads may influence the line impedance that most often is corresponding tightly with the short circuit power of the supplying network. It is especially true for fixed speed motors that decrease the impedance and increase the short circuit power. Furthermore, the damping of the network may be influenced as well (mainly by heating loads).

Changes in the plant supply network are caused by new or additional transformers or just by the way how parts of the plant network are interconnected (e.g. new lines and/or cabling, changes in closed/opened tie-breakers). Such changes primarily influence the line impedance.

In the following the consequences of such modifications and their impact on the plant operation are described.

Plant Power Factor

Usually there are no complaints about increasing the power factor (at least as long as the power factor does not become capacitive – although in most cases even this does not really cause problems). Decreasing the power factor may drop it below the target value that is demanded by the utility and thus may result in costly penalties. Therefore it is recommended to calculate the influence in advance, before the first energy bill with penalties comes in.

Harmonic Distortions

Unlike the power factor, harmonic distortions are more difficult to evaluate. There is no clear threshold for harmonic distortions below which there is trouble-free operation of the plant and above which troubles start to show up caused by harmonics. Even the values given in major standards only indicate acceptable levels based on experience. Neither is the compliance with such limits a guarantee for trouble-free operation nor is a moderate violation of these limits a verdict for facing troubles. However, the violation of international standards or limits given by the utility at the PCC may result in problems for the plant operation and lead to a significant cost impact. Again, it is recommended to perform a network study in advance.

Line Impedance

The line impedance is the topic that is the most difficult of all three mentioned here to observe and to track. In contrast to power factor and harmonic pollution there do not exist clear, direct and accurate ways to measure or to evaluate the line impedance. As a result, the awareness of risk caused by changes line impedance is practically not existent.

Beside the impact of the line impedance on short circuit currents, withstand capacity of equipment and voltage variations, there are specific aspects related to harmonic distortions. Generally, the lower the line impedance and thus the higher the short circuit power, the lower are the harmonic distortions. However, the interdependence is more complex. Even a very strong network with low line impedance cannot guarantee trouble-free operation with respect to harmonics due to so-called parallel resonances where at specific frequencies the line impedance becomes very high. If parallel resonances occur at a frequency where strong harmonic currents are produced by any equipment within the plant or even outside the plant, then exceptionally high voltage distortions may result. Unfortunately the frequency of each such resonance (there are usually several) and the potential for causing serious trouble varies with a number of factors such as short circuit power of the supply network, characteristics and number of transformers, power and type of loads within the plant, interconnections of the plant parts, etc. It is important to point out that especially power factor compensation units within the plant, i.e. capacitors and tuned or detuned harmonic filters, have a big influence.

Hence, relatively minor changes in the plant (or outside of it) may considerably worsen the situation regarding harmonic distortions. Even major failures of important equipment such as main transformers, major cable routes, large motors or electronic equipment have been experienced. The most endangered equipment however are the PFC units that are involved in creating parallel resonances. Explosion of capacitors is a relatively common experience in such situations. Fortunately, such catastrophic results are rather rare because they need a specific combination of circumstances in order to happen. Not only the parallel resonance of the line impedance has to be in a critical frequency range but also the resonance has to be weakly damped (this is the case in low load situations) and large equipment that can magnetically saturate (such as transformers and motors) has to be energized. A huge amount of harmonics in the inrush current of the energizing transformer or motor collides with a high impedance of the parallel resonance. Even worse, the harmonic currents are amplified at frequencies close to the one of the parallel resonance. As a result, 1 A coming from a harmonic source becomes a current of up to 10 A that flows trough a transformer, cable or capacitor.

Practically, all potential problems caused by a change in the line impedance can be prevented by a careful network analysis and a conservatively designed PFC system. However, this is true for the two topics mentioned previously, power factor and harmonic distortions, as well.

Summary and Conclusions

For minerals plants power factor compensation units usually can be economically justified easily. These units reduce the required apparent power and avoid over-sizing of equipment and thus lead to significant cost savings. This power factor compensation equipment is also used to filter harmonics generated from various sources – most often from variable speed drives. When using cycloconverter drives usually harmonic filters are necessary for operational reasons. The high power of cycloconverter drives used for ball and SAG mills in combination with a rather weak network, which is typical for many large mines, would otherwise result in too high harmonic distortions. The interaction between cycloconverter drives and other large drive systems with harmonic filters, network and the plant operation require consideration of many aspects influencing the design of harmonic filters. It needs to be pointed out that many data are not easily available and many crucial design aspects are based on experience. Thus, the design of a harmonic filter system for such demanding applications as minerals and mining plants very much requires a high level of experience and expertise to come up with reliable concepts that fulfill all customer and process requirements and cover all operating conditions.

Problems with harmonics can significantly affect the operation and harm other equipment but are not always obvious. Proper design of new plants, care with replacement of equipment, plant modifications or plant expansions and expert advice can help to avoid or overcome such problems.

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