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EXPANSION AND MODERNIZATION OF AN IRON ORE PELLETIZING PLANT IN NORTHERN SWEDEN

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Abstract

The paper describes the main drive systems of an iron ore pelletizing plant and related important design aspects. It is shown how today's drive systems provide the desired flexibility for the process and lead to high energy efficiency and system reliability. With respect to electric drives expansion projects have many technical issues in common with green-field installations. However, there are aspects where important, distinct differences occur. It is shown which considerations for selecting and sizing drive systems for such a plant as well as for integrating them into an overall plant control concept need to be taken into account. Besides the design of the drive systems a key aspect for such an expansion project is the network interaction. Harmonics levels at different points in the plant network need to be checked carefully with simulations during the design phase to avoid problems later-on during operation. The power factor compensation and the harmonic filtering of the new production line cannot be designed independently of the already existing plant. The paper highlights areas where problems could occur and which points need to be paid attention to when a plant is expanded.

Introduction

In the face of shrinking world reserves of high-grade ores, ores must now be concentrated before further processing. Pelletizing turns very fine-grained iron ore into balls of a certain diameter, also known as pellets, which are suitable for blast furnace and direct reduction. Pellets form one of the best options, thanks to their excellent physical and metallurgical properties. Moreover, due to their high strength and suitability for storage, pellets can be easily transported over long distances, with repeated transshipments if necessary.

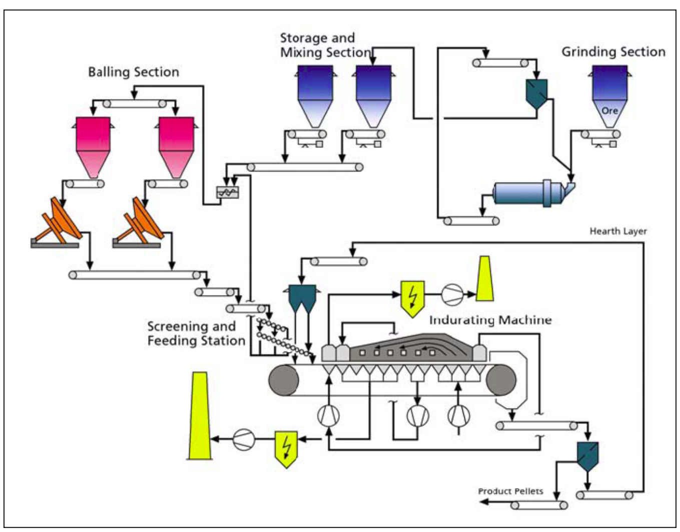

Figure 1. Typical flow diagram of a pelletizing plant [8].

Traveling grate process comprises three steps: raw material preparation, forming green pellets and pellet hardening. On an industrial scale, green pellets are formed either in pelletizing discs or drums. The drums are usually connected to roller screens used for separating undersized pellets (150–250 %) which are returned to the drum. This high level of circulation makes pelletizing drums less sensitive to variations in feed material properties. Pelletizing discs need only a single process step to form pellets, their classifying effect discharging the pellets from the disc rim within a very narrow size range. Since green pellets have low mechanical strength, they need to be hardened for the processes, which will follow. To do this, the traveling grate, best thought of as an endless chain of pellets, is applied. A roller conveyor, for example a double-deck roller screen with each deck separating out oversized and undersized pellets, ensures that only pellets of the right size (generally 9–16 mm) are evenly distributed across the width of the traveling grate. The grate carries the green pellets on a bed 30–50 cm thick through a furnace with updraft drying, downdraft drying, preheating, firing, after-firing and cooling zones. A major advantage of the traveling grate is that the green pellets remain undisturbed throughout the process.

LKAB is an international high-tech minerals group, one of the world's leading producers of upgraded iron ore products for the steel industry and a growing supplier of industrial minerals products to other sectors. Most of the iron ore products are sold to European steel mills. LKAB has more than 3500 employees. There are iron ore mines, processing plants and ore harbors in northern Sweden and Norway [7].

LKAB's strategy to produce pellets was initiated 50 ago with the opening of the first pelletizing plant in Malmberget, a plant which no longer exists, in 1955. Global steel consumption and steel production have increased dramatically in recent years. China is the major driver and strong demand is expected to persist. To increase LKAB's capacity for producing more iron ore products, an extensive program of investment is being implemented, amounting approximately 11 billion SEK. The program includes new pelletizing and concentrating plants in Malmberget and Kiruna, increased capacity in the Kiruna mine and investment in a new ore harbor in Narvik, as well as investments in Logistics. Investments will raise LKAB's delivery capacity for iron ore products from a current 23 million tons to 25 Mt by 2007 and to 30 Mt by 2008.

On 25 October 2006, LKAB's fifth operational pelletizing plant, MK3 in Malmberget, was inaugurated. The total capital expenditure amounts to 2.6 billion SEK and comprises three parts: a new pelletizing plant, expansion of the concentrating plant, and new facilities for loading and discharging at the rail yard. The discharging station was completed first and was commissioned on 3 April 2006. Here, finished products, crude ore, and additives such as olivine, limestone and quartzite are handled. For the first three years, much of the crude ore for MK3 will be supplied by the mine in Kiruna, but eventually, the plan is for the Malmberget mine to meet the entire demand for crude ore for all processing plants in Malmberget. An entirely new section has been built adjacent to the existing concentrating plant, with three grinding stages (mills) and subsequent separation. Section 6 was handed over for operation on 12 September 2006. Originally, commissioning of the pelletizing plant was planned for the turn of the year 2006/2007. Work has progressed more quickly than expected and commissioning has already begun. Initially, production will increase by 2.5 Mt per year. The plant has been built for a possibility for further increase to 4 Mt per year through

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complementary investments when permits are in place for this volume of production. The increase will enable LKAB to retain market shares with key growth customers in Europe and to remain a stable supplier to Nordic steel mills.

The Malmberget mine covers an area of approximately 11 square kilometers (4.5 km east to west, and 2.5 north to south). The mine consists of about 20 orebodies, of which 10 are currently mined. As the orebodies are mined, new main levels must be built to continue mining at depth. In Malmberget, mining will pass the present main level in 2010. In the Malmberget mine, expansion of mining is taking place at the 1000-meter level. At the same time, planning of the next main level, at 1250 m, has commenced.

Drive System Selection

When a drive system is selected for minerals applications, a large number of items need to be checked and many questions must be answered. Depending on the mill size and type, the mill can be driven by several configurations of drive systems. A key decision must been taken between fixed speed and variable speed drives. This selection process is of course plant specific and may be biased by customer preferences or company guidelines. Several factors such as process, mechanical, electrical and cost considerations must be taken into account in the drive system evaluation. Choosing the correct factors is not easy. However, a proper evaluation and the right selection of the drive system are important for the plant design and have a high impact on future plant operation.

For many grinding circuits, variable speed is valuable when circuit feed-rate control is required downstream. Without downstream constraints, mills are often operated fixed speed. However, sometimes variable speed drives have shown to be advantageous in such cases as well because this additional degree of freedom allows process optimization and helps to avoid operational limitations for the future. The mills for the Malmberget processing plants however are fixed speed using slip-ring motors with liquid starters.

In the concentrator section of an iron ore palletizing plant the main drive applications are milling and pumping (slurry pumps, raw water pumps, etc.). In the pelletizing section fans (cooling, drying, exhaust, etc.), compressors and pumps are used.

Beside the desired flexibility for the process today's drive systems provide as well high energy efficiency and system reliability. For pump, compressor and fan applications, variable speed drives can dramatically reduce energy consumption. The power required running a pump or a fan is proportional to the cube of the speed. Thus, a pump or fan running at half speed consumes only one-eighth of the energy compared to one running at full speed.

All fans are provided with their own pressure / volume characteristics, which when plotted graphically, are known as the fan characteristics. Figure 3 shows a typical fan characteristic as a function of pressure and volume flow. Also shown is a typical system characteristic; the point of intersection with the fan characteristic is termed the operating point. If the required volume of air is not as designed, the fan or system characteristic must be changed. Traditionally, the most common way of changing the operating point is by using a damper which alters the system characteristic (shown by the longer broken lines). However, increasing or decreasing the fan speed will change the fan characteristic and hence the operating point.

Modern drive technologies, such as DTC (Direct Torque Control), give even better energy savings as well as more accurate speed and torque control across a wider speed range. Increased energy saving can be achieved with DTC-based drives compared to standard AC drives on pump, fan and other centrifugal applications, as the drive's flux optimization feature reduces the energy drawn by the motor.

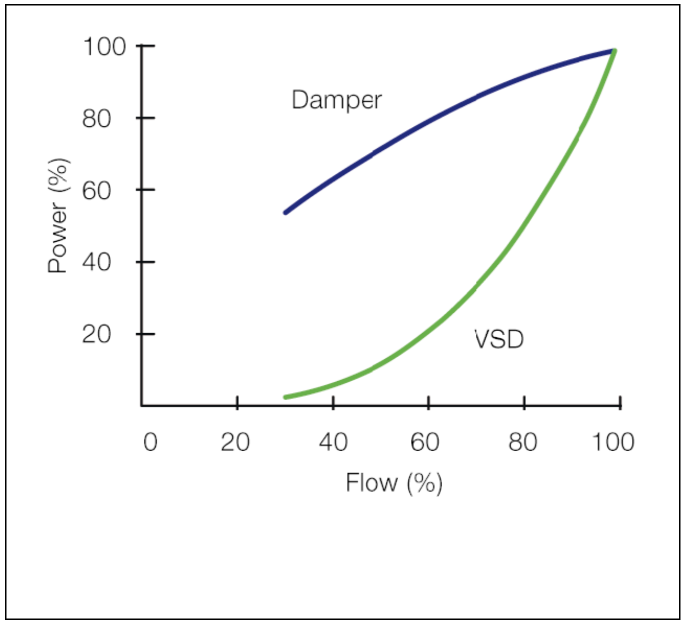

Figure 2. Fan power requirement for damper and variable speed drive.

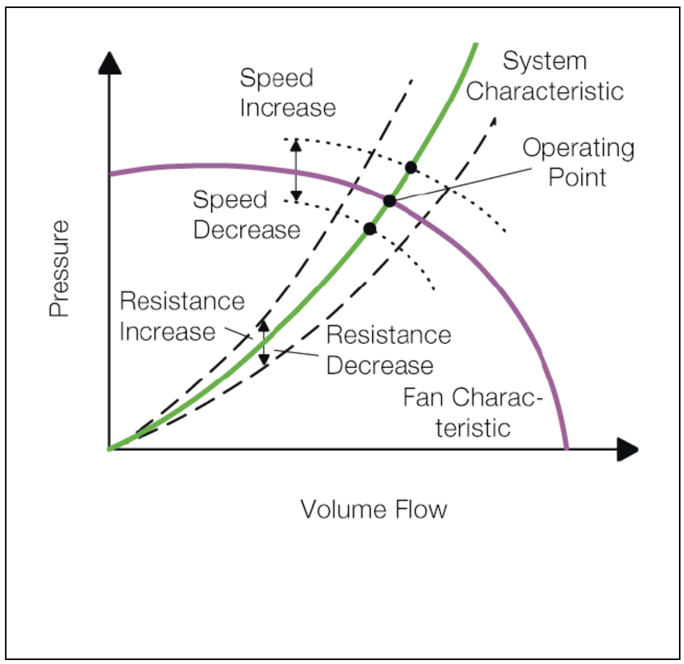

Figure 3. Typical fan characteristics showing the operating point.

Further energy savings can be achieved by using regenerative drives. These drives use the energy produced by a decelerating load. In this case, the spinning load is driving the motor, which acts like a generator, feeding current back to the drive through the supply cables. This means that large energy savings can be achieved in applications where energy from the braking of the motor can be fed back into the network and used by other applications. In addition, large braking resistors, which dump waste heat into the atmosphere, can be eliminated, freeing up floor space and reducing the need for ventilation.

Apart from energy savings, system availability effects productivity and therefore, profitability. In the case of today's drives, these offer not only very high availability of 99.9 % but efficiencies above 98 % too.

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For the Malmberget processing plants more than two-hundred fixed speed motors are installed. These are mainly used for auxiliary drives and lower power applications. In order to gain the necessary flexibility for the process and achieve high efficiency more than one-hundred low voltage and five medium voltage variable speed drives are used.

System Integration

The motivation of most revamp or retrofit projects where drive systems are replaced in existing plants are either to modernize old, out-dated drive systems, to increase the efficiency or to increase the production capacity. These projects usually need a proper drive system selection as well as an evaluation of the specific boundary conditions such as existing mechanical and control interfaces, space constraints, and re-use of existing equipment. Expansion projects where additional production lines are installed have many technical issues in common with green-field installations. However, there are aspects where important, distinct differences occur. In the following some key points that need to be addressed properly are given for the integration of drive systems into both a plant network and a plant control.

Main Circuit Breaker

For medium voltage converters the main circuit breaker is one of the most important devices to protect the whole system in case of a failure. In spite of the high reliability of the drive, faults might happen because of certain unfortunate circumstances like human failure, material defects, etc. In such a situation the correct operation of the main circuit breaker will protect the drive for risks of damages. Therefore a correct operation of the main circuit breaker is very important. The main circuit breaker must be able to connect and maintain nominal load currents and clear short-circuit currents, to tolerate the transformer inrush current without tripping, and to clear transformer primary sides short-circuit instantaneously by breaking the fault current. The main circuit breaker is to be controlled entirely by the medium voltage converter and the closing command for the main circuit breaker must be given exclusively from the medium voltage converter. The closing command will be given upon a closing request to the medium voltage converter control. The closing request or command can be initiated from a local or a remote control location. Manual closing of the main circuit breaker, e.g. directly from the switchgear panel, can cause major damage within the drive system or even risk for human life and is therefore strictly forbidden and has to be disabled. In order to ensure the correct operation of the medium voltage converter under fault condition a maximum total breaking time of the main circuit breaker has to be guaranteed. Breaking time is the defined time interval between the energizing of the opening coil and the extinguishing of the current flow in all poles.

These points need to be considered for every project where new breakers are purchased. However, it is a critical item for revamp projects where only the drive system should be replaced and the existing main circuit breakers should be kept. In such cases it is important to carefully check the suitability of the existing breakers in an early stage of the project.

Cables

Cables are dimensioned on a case-by-case basis in accordance with the local regulations concerning short-circuit protection, operating voltage, permissible touch voltage appearing under fault conditions and current-carrying capacity of the cable. In addition, the cable type must support the EMC protection and availability of installed equipment.

The cables from the main circuit breaker to the transformer primary side got no special requirements with respect to frequency converter operation.

The transformer secondary cables (the cables from the transformer secondary windings to the frequency converter) as well as the motor cables (the cables from the frequency converter to the motor) need special attention. Whether there are special requirements to be considered with respect to frequency converter operation depends on the type of frequency converter and the use of output sine filters. If the cable type is not selected correctly and complying with the frequency converter requirements then problems with common mode voltages resulting from normal inverter operation, with bearing currents or with EMC may occur. It is therefore necessary to check the cable specifications of the supplier of a frequency converter and follow the given recommendations and guidelines. These documents describe the correct cable type, its shielding, screening, termination, grounding, protection, insulation rating and the maximum cable length.

De-rating of cable ampacity in accordance with maximum expected ambient temperature, raceway fill factors, and any other factors required by local electrical codes should be applied.

If existing cables should be used when revamping drive systems these points need to be checked carefully to make sure that the existing cable type is suitable for the planned frequency converter operation.

Other Aspects

Space constraints and boundary conditions due to an existing infrastructure (e.g. existing cable channels, the height of buildings, door sizes and transportation and lifting devices) may need to be considered and may have an impact on the design of the new equipment, especially for drive system revamps.

When installing drive systems into an existing plant product harmonization may be considered in the selection process. It may be desirable to have a limited number of products in use in order to acquire and maintain the necessary knowledge and experience within the operations and maintenance personnel, and to optimize service and maintenance. With such an approach the number of spare parts that need to be kept on site can be reduced as well.

When an existing plant is expanded or specific drive systems are replaced then changes in the drive communication to meet the plant control system standards seem to be the appropriate approach. The existing plant control software can still be used without major modifications. The design and programming work for the drives supplier is most likely much smaller compared with the work that would be necessary to modify the plant control. Furthermore, operations and maintenance personnel are used to the existing control philosophy and different solutions within a cement plant can be avoided.

Support for service and maintenance can be given by the supplier locally as well as centrally from the center of excellence. Local support has advantages with respect to response time (no time zone difference, less travel), administration (visa, health and safety regulations, permits) and language. On the other hand the central unit has a much deeper knowledge, much more experience and a larger number of experts available. The central unit is also responsible for the training of the local service engineers, and assures information exchange and quality control throughout the organization. For the Malmberget processing plants the commissioning of the drive systems was done by local service and commissioning engineers with training and support from engineers of the center of excellence. With this approach the necessary competence was built up locally in Northern Sweden to provide fast service and trouble-shooting to the customer.

Overview of Harmonic Filter and Power Factor Compensation Systems

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,

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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. Over the last years variable speed drives have been used more often. 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. 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.

The best option to fulfill the requirements for harmonics as well as for power factor 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 impedance. 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 4 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).

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 4 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.

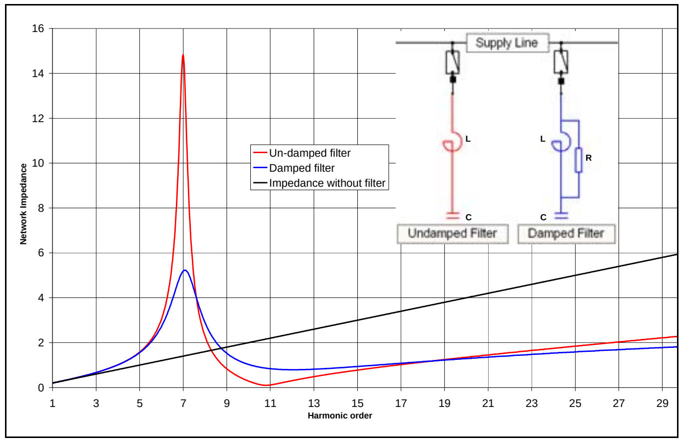

Figure 4. Parallel resonance and the effect of damping of a harmonic filter

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 a 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 4 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 4 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 4 it can be

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seen that the blue curve at the 11^{th} harmonic has considerable higher impedance than the red one that almost has zero impedance.

General Design Aspects of Power Factor Compensation and Harmonic Filtering Systems

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 5^{th} and 7^{th} harmonics are the highest harmonic current levels, a single filter tuned close to the 5^{th} 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.

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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.

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.

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.

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.

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.

Specific Design Aspects of the Power Factor Compensation and Harmonic Filtering System

The main goals of the PFC systems at the Malmberget processing plants were to improve the over-all power factor at the Point of Common Coupling (PCC) for the new plant to value • 0.96 lagging, measured as hourly and monthly averages, to reduce the voltage harmonic distortions caused by harmonic sources within the new plant according to IEC standards, and to keep the voltage step-change due to switching of the PFC units • 3 % of the nominal bus voltage. In addition, sufficient damping of parallel resonances (caused by filters, external capacitors, and cable/line-capacitances) should be

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achieved in order to avoid adverse effects on electrical equipment within the plant. Where technically possible and economically reasonable, filter components should be rated and designed so that the spare part inventory can be substantially reduced. The number of PFC units should be minimized in order to improve reliability of the PFC and to keep investment cost minimal.

During a short plant visit measurements were carried out as a part of the data collection. The existing plant and the new plants can be interconnected through different MV links. All cables, lines, and transformers modeled in the study, are defined by data given in by the customer in single line diagrams or collected during the plant visit. The network consists of different types of overhead lines and cables in the existing plant. Appropriate values for the line/cable capacitance are assumed and included in the model. The lengths of these cables/overhead lines are taken from the plant single line diagram. Cable data for the interconnection of the new plant with the HV network is also considered in the network model.

All variable speed drives within the existing plant as well as all variable speed drives within the new plant are considered for the analysis. For the LV and MV drives specific current harmonic spectrums have been considered. These are based on typical, theoretical values (e.g. "standard 6-pulse spectrum") as well as on experience and measured data for such drive systems. For sub-synchronous cascades amplitudes are considered from both sets of harmonics: the "normal" one (with fixed frequency for each harmonic) and the "moving" one (with decreasing frequency for each harmonic as the drive-speed increases).

All the major motors indicated in the existing plant single line diagram are considered in the network model. The motors for the primary mill, secondary mill and the tertiary mill are implemented in detail in the network model, since they are of considerable size and influence on the impedance of new concentrator bus. The PFC units / harmonic filters in the existing plant have considerable influence on the impedance of the feeding network and therefore have been included in the network model as well.

These PFC units have been planed and realized in different stages of the plant development and thus there is no coherent concept for the PFC system in the old plant. This is the reason why under certain combinations of plant and network conditions serious troubles may occur. In order to check the effectiveness of proposed harmonic filters for the plant expansion, a large number of study cases have been performed for the different operational conditions of the plant and the supplying network.

For achieving the target power factor of 0.96 for the new plant at the 145 kV voltage level, approximately 16 MVAr capacitive power is needed. However, in order to fulfill harmonic targets and to provide consistency and identical capacitor can sizes a slightly higher compensation power has been selected. This total capacitive power has been divided in to MV and LV PFC units. The PFC units at the LV busbars have primarily the function to keep harmonic distortions within the limit, and only secondarily to improve the power factor of the LV loads. Therefore, not all of the LV busbars have PFC units attached to them. The power for LV PFC units has been minimized due to following:

- Cost: The kVAr price at LV is at least twice the price for the same power at MV.
- Efficiency of harmonic reduction: MV filters are more efficient in this respect.

For the new concentrator plant the harmonic distortions at the MV bus have not been a critical issue, due to relatively small amount of harmonic sources being fed from this bus. Therefore care has been taken to reach the targeted power factor and to avoid building risky parallel resonances. The optimal solution fulfilling both requirements is only one C-type PFC and filter unit that is tuned for the 3rd harmonic. This leads to a strong damping with virtually no 50 Hz losses in the damping resistor (no operating cost), fits optimally to the recommended LV PFC units and lowers all harmonics with order 3 and higher.

For the new pelletizing plant the harmonic distortions have been a critical issue, due to relatively high amount of harmonic sources being fed from this bus. Therefore care has been taken of the harmonic distortions. Two PFC and filter units have been designed, one C-type PFC and filter unit tuned for the 3rd harmonic and another HP-type PFC and filter unit tuned for the 5th harmonic.

Similar to the new concentrator plant, harmonic distortions at this MV bus of the existing concentrator plant have not been a critical issue. However, the main difference is the presence of existing MV filters. They introduce an un-damped parallel resonance in the frequency area between 3rd and 4th harmonic. This behavior needs to be considered in the design of the PFC and filter unit for this part of the plant.

An existing capacitor bank connected to the 21 kV bus has been considered to be a potential risk. By adding new MV components to the existing C-bank such as auxiliary capacitors, series reactors and damping resistors the C-bank becomes a tuned and damped C-type filter. This eliminates the risk of parallel resonances and its potentially disastrous effects, and reduces harmonics. The damping will be beneficial in case of transient events on the network but adds no operational cost for the damping, because the auxiliary capacitor allows operation with virtually no 50Hz losses. The existing C-bank will be less loaded with harmonics whereas the effective capacitive power of the existing C-bank will remain unchanged.

One of important cost factors in design of PFC and harmonic filter systems is the number of PFC units. The smaller their number, the lower is the cost. Therefore care has been taken to find the PFC system with the minimum number of units, which are still able to fulfill all the major requirements. Furthermore, one of the design criteria for PFC units was to minimize the number of different types of components, creating a minimum amount of hardware needed for spare parts. E.g. the filter Set “F3/4.6/6.3”, “F3/3.1/6.3” and “F3/7.7/6.3” have identical capacitor cans for both main and auxiliary capacitor banks. The damping resistors are also of same rating for these filters.

The filter components have been designed carefully and conservatively in order to assure filter operability even under conditions which were not considered in the study. However, some extreme conditions may cause the filter protection to trip.

Figure 5. Filter unit installed at Malmberget processing plant

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It is recommended to keep all filters connected continuously. But if filters need to be disconnected for any reason, the order defined in the switching concept has to be followed. The switching concept follows the general rules given above in the general design aspects considering the installation specific requirements. The switching philosophy is critical when switching different filters on the same MV busbar or on the busbars that are directly coupled through MV bus couplers.

Summary and Conclusions

Expansion projects have many technical issues in common with green-field installations. However, there are aspects where important, distinct differences occur. When selecting and sizing drive systems for such a plant as well as when integrating them into an overall plant control concept additional points such as re-use of existing equipment, product harmonization, spare part concepts as well as service and maintenance need to be taken into account.

Besides the design of the drive systems a key aspect for such an expansion project is the network interaction. Harmonics levels at different points in the plant network need to be checked carefully with simulations during the design phase to avoid problems later-on during operation. The power factor compensation and the harmonic filtering of the new production line cannot be designed independently of the already existing plant. 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. 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.

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