NEW LIFE FOR OLD POWER RECTIFIERS

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I. INTRODUCTION

Many operators of Chlorine plants are faced with the challenge of working with vintage rectifiers. Replacement is seldom justified unless it is part of a major plant expansion.

Nevertheless, many old rectifiers have significant reliability problems that cause major downtime. This paper outlines cost-effective methods of improving dependability, power output and the useful life of old rectifier equipment.

The paper begins by outlining the most common types of rectifiers used in the chlorine industry. Shortcomings and issues of concern are noted. Two case studies of retrofitting the controls on the two most common types of rectifier are presented in detail. Finally, brief descriptions of three other rectifier upgrades are presented.

II. RECTIFIERS 101

Some basics of how high power rectification is done.

Three types of rectifiers are used in the chlorine industry. All three are semiconductor based. Diode and thyristor rectifiers are common and have been in use for over 40 years. DC choppers are a recent addition for large electrochemical applications and several have been installed in the last few years.

A. Diode Rectifiers

The basic element that converts alternating current (ac) into the direct current (dc) current that is needed by electrochemical cells is a diode. A diode operation is very similar to a one-way check valve. It allows electrical current to flow in only one direction. In fact, outside of North America semiconductors that are used for rectification are called “valves”.

Semiconductor development typically starts with small signal devices used in communication and other low power applications. As a result, diodes had been in use for more than a decade before relatively large power diodes were developed. The first diode rectifiers for electrochemical production appeared in the mid-1960s. These early machines required massive paralleling of diodes to obtain the tens of thousands of amperes required. Often a rectifier of this vintage had up to 500 or more diodes operating to provide the required output.

As with a check valve, diodes are either on or off. A method of controlling current is necessary and a regulating transformer with on-load tap changers is typically used for coarse control of a diode rectifier. For fine control, saturable core reactors are often used. These magnetic devices “throttle” the current in order to smoothly regulate it over a short range.

On-load tap changers are complex mechanical devices that are expensive to produce and require ongoing maintenance. Although saturable reactors have a high initial cost, they are reliable, particularly when mounted outside the transformer, and they do not need much maintenance. However, the saturable reactors introduce additional losses even when the reactors are not actively controlling current.

That said, many of these mid-1960s diode machines are in operation and continue to provide adequate service although many are now approaching double their design life of twenty years.

B. Thyristors (SCRs)

Thyristors were introduced to high power rectifiers in order to increase energy efficiency, operating speed and accuracy of control.

The thyristor followed the same development pattern as other power semiconductors. Invented in 1957, it did not reach the users of industrial power rectifiers until the end of the 1960s. It has been the dominant device for large power rectifiers for thirty years and is still the technology of choice when equipped with modern digital electronics and control methods. Contemporary thyristors are rated for several thousand amperes each. Thirty years ago a typical thyristor would carry a maximum of 200 to 300 amperes.

A thyristor is a power diode with a gate control terminal added. Energizing the gate earlier or later determines the average voltage applied to the cell line. If the cell line impedance and temperature is considered constant, along with other process variables, then the average amount of current delivered to the cell-line is varied as the voltage

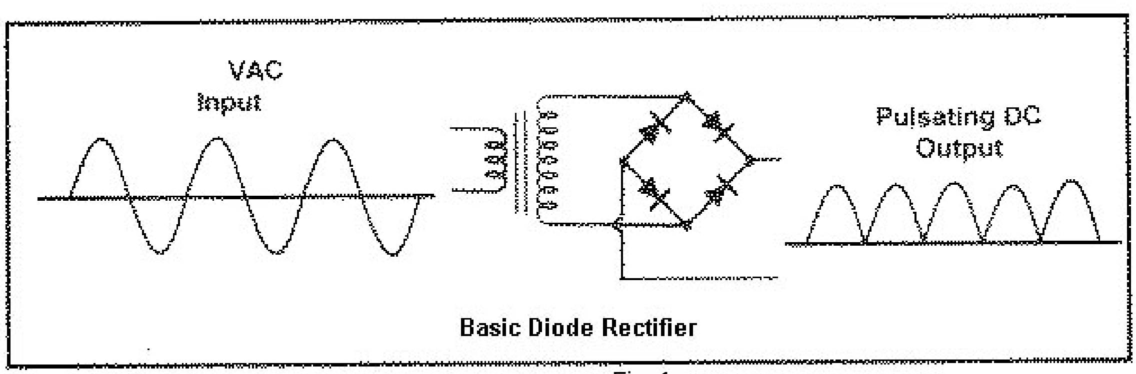

Fig. 1

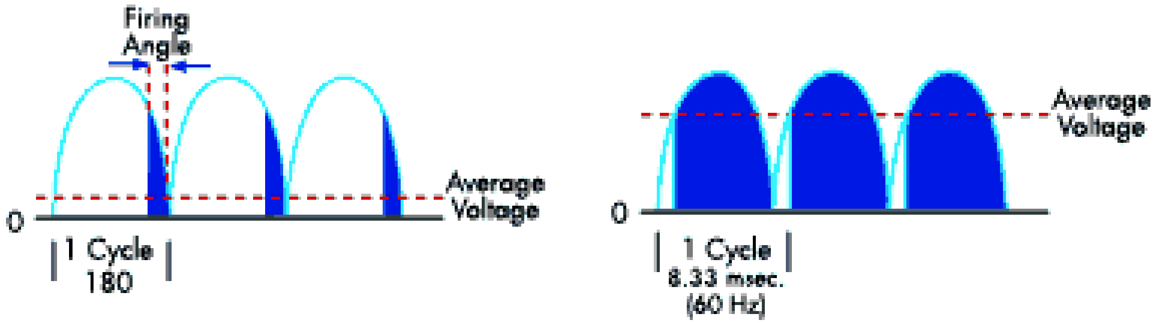

Fig. 2

changes in accordance with Ohm's law. The control of current in by this method is termed *"phase control"* as shown in Fig. 2.

A relatively small energy pulse to the gate triggers the thyristor on. A typical value to turn on a 2,000-ampere thyristor is 500 milliamperes at 10 volts for 10 microseconds. Timing of the triggering is critical for optimum operation, particularly for parallel-connected thyristors. The more devices paralleled, the more important the timing. This issue is addressed in more depth later in the paper.

The thyristor rectifier gained favor in the electrochemical industry as it eliminated the requirement for an on-load tap changer and saturable reactors. It also provided more precise control over a larger operating range than the diode machines.

As with all solutions, the thyristor rectifier has its drawbacks. Although capable of a very wide range of current output, economic considerations make operating far below its rated output expensive at the high power outputs typical in the chlorine business.

The major problem is a low power factor and its associated power system harmonics. Most power utilities have a billing structure that severely penalizes the customer for low power factor loads. In a poorly designed system, harmonics can cause a variety of problems for both the consumer and the power utility.

The biggest challenge for users of old thyristor machines is maintaining the control (triggering) electronics. Older analog control electronics triggering precision tends to drift due to thermal and other aging problems. When this happens, thyristors start failing, sometimes in a catastrophic cascade manner.

C. DC Chopper Rectifiers using IGBTs

In order to address the deficiencies of thyristor current control range, manufacturers have introduced a new high power rectifier to the market.

Dc-dc converters, otherwise known as dc chopper rectifiers, have attracted a large interest in recent years. The chopper is not a new idea and has been used for dc motor drives using thyristors for many years. What is new is the use of *"Insulated Gate Bipolar transistors (IGBT)"* combined with microprocessor control to implement "*pulse width modulation (PWM)"* control. These devices and a whole series of similar devices in development have already made the ac motor variable speed drive economical and ubiquitous.

The dc chopper rectifier uses an unregulated diode front end to convert ac into dc. At this stage, it is not different from the diode rectifier discussed above. The IGBTs control the dc current output by adjusting average output voltage. A dc-dc chopper is often described as a dc transformer. That is, the chopper either steps the voltage up or down with a corresponding change in output current.

This flexibility in controlling the output makes the high power dc-dc chopper very attractive. Other attributes of dc chopper rectifiers include:

- High power factor; more than 0.9 over the operating range without auxiliary power factor correction equipment;
- Higher efficiency over the complete operating range;
- Lower harmonic levels particularly when running at reduced loads;
- Fast dynamic response;
- Simplified transformer design and lower costs, offset somewhat with greater complexity of electronics and additional losses due to two sets of semiconductors – both diodes and IGBTs are used;
- Low output ripple.

The choppers greatest advantage is its flexibility and cost saving when the process requires large changes in load current. Because the loads in the chlor-alkali industry are relatively constant, unlike, say the plasma process, a close evaluation is required to see if a chopper application is warranted.

One issue that requires careful engineering with a chopper system is the dc bus supplying the cells. Due to the large amount of output capacitance a chopper uses, the inductance of the bus can create a filter that can make the chopper system unstable. Other concerns are the IGBT's electronic complexity and the requirement to parallel devices to obtain sufficient output current.

That said, several chlor-alkali plants have successfully installed choppers.

III. Power Factor and Harmonics

A. Power Factor

A power factor (PF) penalty is a borrowing fee imposed by your supplier of electrical energy. The power company charges you for the electricity you borrow and do not

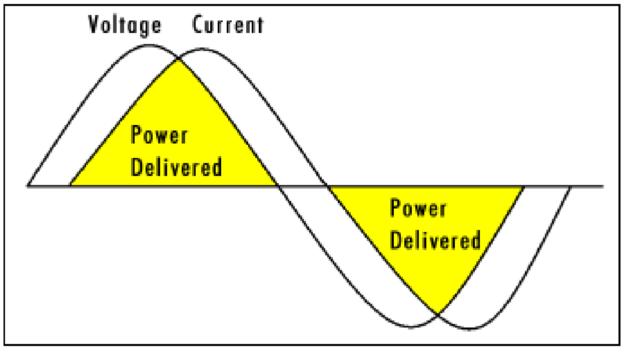

Fig. 3

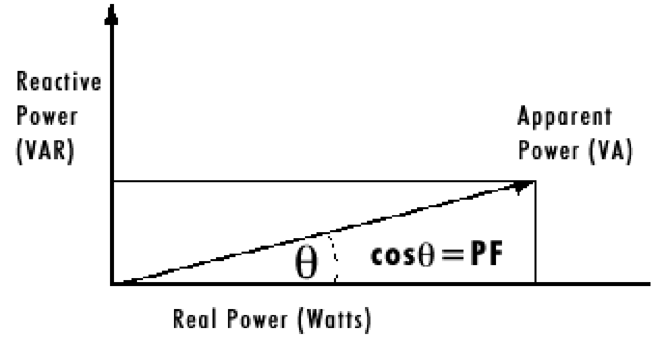

Fig. 4

consume. What this means is that the rectifier system draws *reactive* power from the system but does not consume it. It acts somewhat like a spring where energy is used to compress the spring, which stores the energy and then returns it when the spring is released. The electrical analogy of a spring is an inductor, or the magnetic circuit of the transmission system and rectifier transformer as the electric current alternates and changes polarity. In a circuit with inductance, a time lag exists between when voltage is applied and current flows.

The power that the system demands and then sends back is called *"reactive power"* whereas the actual power consumed is called *"real power"*. Shown in Fig.3 is the time lag between voltage and current. The shaded area is the real power delivered. The total area under the both curves represents "*apparent power",* which is the sum of reactive and real power. The area outside the shaded area represents the borrowed or reactive power.

The cosine of the angle shown in Fig. 4 between the real and reactive power is a number between 0.0 and1.0. Utilities vary in the policy when to charge a PF penalty. 0.9 to 0.95 are typical with more and more utilities switching to a kilovolt-ampere billing structure. When power factor drops below one, they charge for it.

The reason is that even though the user does not consume the power but only draws it and then sends it back, the utility charges for the infrastructure needed to supply the borrowed power.

To control the current either with saturable reactors or by varying the triggering of thyristors causes a further drop in power factor. The cause is the additional delay between the time the voltage is applied to the diode or thyristor and the time the current starts to flow, similar to the time lag described above for magnetic components. For thyristors this delay time is referred to as *"angle of retard alpha (α)".* Thyristor rectifiers usually have a minimum angle of retard of about 12 electrical degrees.

To give the system a useable range of currents and avoid PF penalties, capacitors are often used to supply the reactive power needed system at the rectifier. Capacitance counteracts the effects of inductance in the system and supplies the reactive power required by the rectifiers.

B. Harmonics

In North America, normal ac power alternates at 60 cycles per second or *Hertz (Hz).* The ac input to a rectifier is not sinusoidal. It is a stepped rectangle. The deviation from a smooth sinusoidal waveshape is called *"distortion"*.

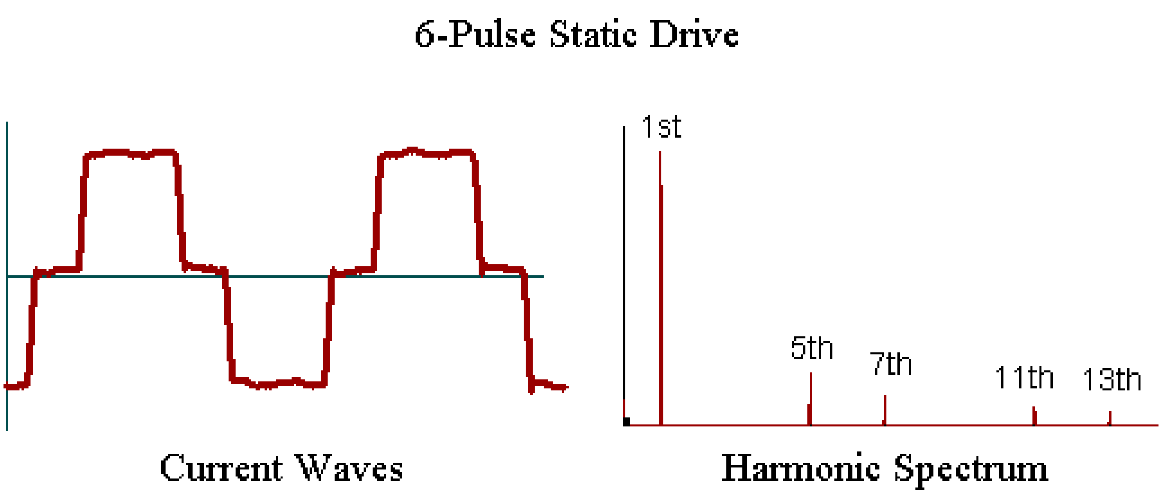

Fig. 5

Fourier analysis shows that any waveform can be resolved into a series of sinusoids of various frequencies. These frequencies for the electrochemical rectifiers are integer multiples of the 60 Hz frequency. Depending on the configuration of the rectifier typical harmonic frequencies are 5, 7, 11 and 13 times the fundamental frequency of 60 Hz. Harmonics are simply a way of describing the distorted waveform caused by rectification.

Note that power factor is actually made up of two components. *Displacement factor*, which is the power factor previously described and *Distortion Factor*. Rectification creates an input waveform that is no longer sinusoidal but close to a rectangular wave as shown in Fig. 5. The ratio of a 60 Hz sine wave to the harmonics frequencies that make up the rectangular wave is called the distortion factor.

Electrical systems are designed for the fundamental frequency (60 Hz). Harmonic currents cause overheating problems and are a particular problem for any capacitors connected to the electrical system. As harmonic frequency increases, capacitors act more and more like a short circuit to the harmonic currents. Eventually, the capacitors will overheat and fail. Another major problem with rectifier circuits is how harmonic currents can confuse the control system and cause it to become unstable. But, by far the worst problem with harmonic currents is resonance. If a harmonic frequency coincides with a point where the capacitive reactance and inductive reactance are equal, a pulsing energy transfer begins that can tear equipment apart.

As a result, harmonics have a bad reputation. Many people poorly understand them but the methods to treat them are well known and careful engineering of the rectifier power system will avoid all the potential problems.

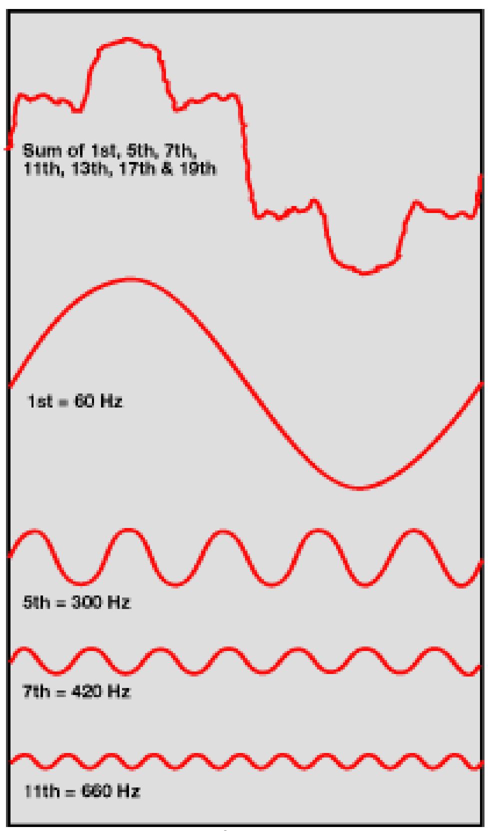

Fig. 6

The make up of a typical ac side current waveform with the individual harmonic frequencies that sum to make is shown in Fig. 6.

For instance, power factor capacitors are purposely combined with a reactor to form a series filter shown in Fig. 7. The filter *tunes* the system so that any harmonic currents are drawn into the filter, protecting the rest of the system. The filters are designed to eliminate the overloading problems of plain capacitor banks.

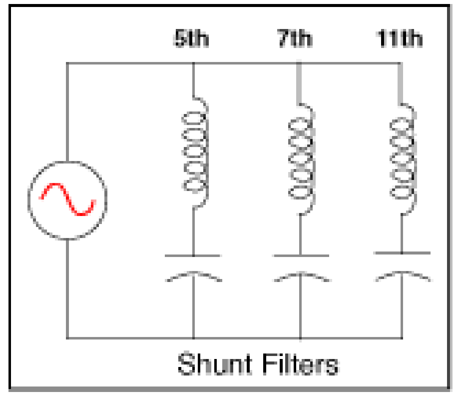

Fig. 7

IV. New Life for Old Rectifiers

The remainder of this paper describes examples of how rectifier performance was improved and rectifier life was extended. Two case studies are presented in detail. Three other examples of rectifier upgrade are presented more briefly.

A. Case No. 1 -New Life for Old Thyristor Rectifiers Using Modern Digital Control

For one chemical plant, the dependability of 1970s first generation thyristor power rectifiers was particularly troublesome. The worst of the older thyristor units required costly ongoing repairs. Production losses were substantial with repeated failures and extended downtime, particularly during periods of full load production.

Despite these problems, plant management was reluctant to replace the equipment based on poor reliability alone. The perceived benefit was not sufficient to overcome the high capital cost and lengthy production outages to install new equipment. Increasing the plant's product output was the key element in justifying funding for this project.

This case study summarizes how increased output and reliable production were achieved at a reasonable cost without replacing the rectifiers.

The plant operates two 52 kA, 275 Vdc output, 13.8 kV input, industrial-type, outdoor water-to-air cooled rectifiers, each supplied with a close coupled forced-air cooled oil insulated transformer. The single way rectifiers consist of 144 thyristors each. Controls were original first generation electronic design using discrete analog components with gate drive and isolator cards mounted in the power cabinet.

1) Background: Aging analog control electronics were particularly troublesome. After some twenty years of operation, repeated random failures of components were increasing in frequency. The manufacturer was no longer in business and replacement parts were not readily available. Drawings of existing circuits and components had degraded over time. Reverse engineering and outsourcing of replacement cards were costly and time consuming. Many repairs required special knowledge that was not available locally.

Automatic load control no longer functioned. The operators regularly adjusted potentiometers in response to process changes.

Similarly, the integrity of the fuse/thyristor failure monitoring system was questionable at best, making identification of failed components a laborious process. When faced with failures or impending problems, the electricians had to shut down the rectifier and manually check the condition of cards, and up to 144 fuses and thyristors. Furthermore, without a first-out thyristor alarm, the operator would not know that load needed to be reduced to protect the remaining thyristors. This greatly increased the probability of cascade thyristor failures and rectifier outages.

Over the years, the make-up of fuses and thyristors had become a mix of manufacturers with unmatched characteristics. The integrity of the fuses had degraded from aging and the fuse-thyristor-bus connections were overheating from variable assembly methods. As a result, current sharing problems between the thyristors were common. Equal current sharing is critical for continued operation of the thyristors. If one thyristor conducts much more than its rated current, it will fail and cause overloading of adjacent parallel-connected thyristors. This quickly leads to a catastrophic failure of the rectifier.

2) Objectives: The objectives of the rectifier upgrade were:

a) Provide current output of 105% of nameplate rating.
b) Reduce unscheduled outages to the point where production levels are unaffected.
c) Provide documentation, and replacement parts sources to facilitate in-house maintenance and troubleshooting.
d) Provide a source of readily available outside technical support.
e) Fit the new controls into the existing control cabinet. Mate up the firing and fuse monitoring equipment to the columns in the power cabinets. Make the operator interface compatible with the old control panel.
f) Limit plant downtime to install the new equipment to ten days per rectifier.
g) Keep one rectifier operating during the upgrade of the other.
h) Obtain a rapid return on investment.

In addition, the following want list evolved:

a) A digital control system was preferred for its stable operation and ability to deliver precise thyristor firing timing, a serious shortcoming with the existing analog controls.
b) Implement the control system in software with user-friendly programmable parameters such as online diagnostics to allow planning for scheduled maintenance.
c) Automatically monitor and alarm the condition of the thyristor fuses. Automatically reduce load or trip the system based on the number of thyristor circuit failures.
d) Replace mechanical auxiliary relays, meters and interface devices with digital devices.

3) Considerations: The major unknown at the beginning of the project was the continued viability of the rectifier transformers. The condition of these costly units was a major criterion for a successful retrofit. Current and past dissolved gas analysis reports and an internal inspection helped to confirm the integrity of the transformers.

The power section of the rectifier was in surprisingly good condition despite the repeated thyristor failures. The thyristors and fuses, although unmatched, were of a style in current use and commonly available. Auxiliary components of the rectifier, including the cabinets, heat exchangers, plumbing and fans, were also in satisfactory condition. The operating history of the plant clearly indicated the necessity of replacing the control electronics with something maintainable. The operator interface consisted of a partially functional alarm panel, broken trend recorders, and worn manual potentiometers. All needed replacement.

4) Gaining Project Approval: Approval for the upgrade hinged on the payback available if production could be increased. The compelling question was whether the system was capable of additional output. Evaluation of the transformers and cooling system history indicated that overheating was not a problem. New, precise control of thyristor firing and careful matching, installation, and thermal monitoring of components would provide better balance and lower operating temperatures. A first-out or high temperature alarm and automatic cutback in case of a thyristor failure would likely allow 105% output without reducing long-term reliability.

5) New Control System: The new equipment consists of controls, gate drive panels, fuse monitoring circuits and a remote digital operator interface. The control panel mounts on a wall within the control cabinet. The heart of the system is an industrial PC. Control system program changes are accessible by a laptop computer that modifies “sequencer” software, a soft PLC type ladder logic.

Each rectifier control is provided with a current regulator of the proportional and integral (PI) type. The current regulator operates with a fast inner feedback loop and a slower outer loop. The regulator has a direct input to suppress firing signals. By going directly to the regulator, a very fast method of stopping firing under fault or emergency conditions results. In fact, the manufacturer’s tests indicate that this action will stop firing faster than the primary 15 kV breaker can open if a tripping signal occurs. Glass fibers transmit firing signals to the thyristors. The control system is shielded and equipped with an LCD display and minimizes the effects of the surrounding magnetic field on the display.

The gate drive, fuse monitor and protection circuits for each phase (total six per rectifier) are mounted on panels attached to the base of the columns in the power cabinet.

An optical glass fiber serial interface connects the control system to the remote digital input panel, where a keypad is mounted for operator input signals. The Remote Digital Input Panel is mounted behind the existing operator control console. A video monitor mounted in a shielded box recessed into the control console displays control, metering and alarm information to the operator. The annunciator is equipped with 160 programmable and 128 predefined points for faults and alarms. Diagnostics include predefined and programmable annunciator messages displayed on an LCD display. Input/Output consists of digital and analog signals. Up to 20 “meters” and 16 “status lights” can be programmed and displayed on the monitor.

6) Results: Benefits of the new control system include better current balance between rectifying devices, slightly cooler transformers and greatly reduced thyristor failures. The plant has adopted a structured procedure to buy, install and monitor thyristors and fuses. This will help ensure current balance and minimize future thyristor failures. Matching the impedance of thyristors and fuses for each leg was critical for the planned increase in output.

Digital control and the use of fiber optics improved the accuracy and precision of thyristor firing. Matching of components and ensuring proper operation of the cooling systems contributed to additional output. On the final day of commissioning, the rectifiers reached full load. The load was increased to 105% the following day. The rectifiers have run constantly since that time, except for the time taken to replace one control card that failed shortly after startup.

7) Suitability for Other Application: A control system upgrade is a very cost-effective solution for improving the output and reliability of older thyristor rectifiers. To assure a successful rectifier upgrade, the following conditions should be examined:

a) The condition of the rectifier transformers is critical. A rewind or major repair is costly and time consuming. Rectifier transformers are usually custom-built, with a complex configuration; these transformers are difficult to source on the “used” market.

b) A history of dissolved gas analysis and an internal inspection is very helpful to the decision making process. Records from the original manufacturer can provide valuable design information when evaluating the transformers potential for additional output.

c) Condition of the enclosure, cooling systems, balancing reactors, maintenance history, operating environment and the original rectifier design constraints are all important considerations. In some cases, it will be less expensive to replace the rectifier and/or transformer.

d) To sustain the intended long-term operation of a retrofit, it is critically important that the plant stakeholders take ownership and understand the importance of performing preventive maintenance, stocking sufficient spare parts and maintaining technical support contacts.

8) Final Comments: The feasibility study was completed in the summer 1997 and the upgrade was completed in the fall 1998. To date, rectifier operation has been reliable and the increased current output has been maintained. Up-to-date digital controls supported by the implementation of practical preventive maintenance methods made the rectifier retrofit project successful.

B. Case No. 2 – Control System Upgrade of a Four-Frame Diode Rectifier equipped with original 1957 Transformers.

This chlorine producer had a diode rectifier in operation that was originally installed in 1957 with Mercury Arc Rectifiers. In 1970, this machine was converted to diodes. Saturable core reactors for fine current control between steps of the transformer on-load tap changers were also added. Since then, various components have been rebuilt, most recently the cooling system. The existing controls were 1970 vintage and in poor condition. The automatic current control feature was inoperable.

The plant’s engineering and maintenance staff managed to keep this equipment operating reliably for many years past its normal lifespan. Nevertheless, time was exacting its toll and the plant had an ongoing battle to keep the transformers operating. One of the biggest problems was oil leakage in the transformer low-voltage bushing area due to localized overheating. Following the normal practice in the chlor-alkali industry, the rectifiers were operated for many years above their nameplate rating. In recent years, this was no longer possible as it was hard enough to keep the rectifier going at below its nameplate rating.

A study was conducted to see what could be done, short of a complete replacement of equipment.

1) Background: Previous work with older diode machines had demonstrated a peculiar and consistent trait. A very common configuration for diode rectifier transformers is four output windings consisting of two delta connections and two wyes, with each supplying a group of diodes. In this case, each winding supplied a frame or individual indoor rectifier enclosure - effectively four rectifiers running in parallel. Each rectifier was rated at 8 kA for a total output of 32 kA.

The rectifier control systems could not balance the four windings and obtain 100% output from all four windings. Typically, the deltas would be operating at 100% output and the wye-connected rectifiers at 90%. The control system did not have the range to balance the rectifiers using the saturable core reactors.

This was important for several reasons. The most significant was that maximum output could not be achieved without overloading half the rectifier system. More importantly, the current unbalance had a number of harmful effects on the equipment, including excessive harmonic generation. Harmonics affect many things, including control system stability. In other words, the control systems inability to control load current precisely created a problem that in turn made rectifier operation even worse. This is typical of harmonic problems in electrochemical plant power systems.

The current unbalance created overheating in the transformers due to incomplete cancellation in the various magnetic fields and the production of uncharacteristic harmonics currents.

The upgrade project proposed the installation of a digital, PLC based control system to replace the 1970 analog controls.

2) Objectives: The objectives of the rectifier upgrade were:

a) Restore automatic control and extend the useful life of the rectifier.
b) Regain the lost output due to lack of control precision.
c) Eliminate obsolete equipment no longer supported by manufacturers.
d) Eliminate unexplained and spurious control actions by moving logic from antiquated hardware to software where it can be easily tracked, logged and revised as necessary;
e) Allow remote monitoring and control.
f) Obtain a rapid return on investment.

3) Selection of New Equipment: Use a PLC to implement the digital control system. Use the PLC to handle both digital and analog input/output signals.

Replace the original saturable reactor preamplifier controls with tracking power electronics.

Use a Liquid Crystal Display (LCD) screen with a keypad for operator inputs. The LCD would monitor rectifier status and document alarms and trips.

4) New Control System: The control system was designed to:

a) Balance current between the four rectifier (A, B, C, and D) frames,
b) Maintain total output of A, B, C and D rectifiers at set point by adjusting the tap changer and saturable core reactors.
c) Provide delay logic to adjust the current output and prevent a race between the tap changer and reactor control action.
d) Compare totalized current output and individual current output and alarm if out of range.
e) Design a rectifier current overload and overcurrent protection function. At a preset overload level, start the transformer tap-changer stepping down. At a higher overload, trip the rectifier after a set period. At double the maximum rated output, trip the rectifier instantaneously.
f) Have a manual mode in case of automatic constant current control (ACCC) system fails.

In addition, an alarm system was needed to notify the operator of:

a) Disagreement between totalized output current and individual rectifier frame currents;
b) Load currents above 9.5 kA per frame;
c) Automatic initiation of a tap changer step-down operation from overload or overcurrent conditions;
d) Startup lockout;
e) Loss of utility power.

5) Control Description: The rectifier current controller consists of two control loops, an inner loop to control the balance between rectifier frames and an outer loop to adjust overall current output. The saturable reactors are first used to adjust current and when out of range, a tap change is initiated to bring the reactor control back into range.

6) Results: The new control system was installed and commissioned in one week during the plant's annual maintenance outage.

A few hours were spent tuning the system for dynamic response, testing the protection systems and ensuring smooth transfer between manual and automatic operation.

There was a problem with one of the saturable core reactors. The insulation had deteriorated and a dc-offset voltage was imposed on one of reactor control winding. Once this problem was corrected, the control system settled down and ran trouble free.

This glitch stresses the importance of closely checking the condition of the major components of a retrofit. Furthermore, as with the thyristor rectifier upgrade, the condition of the transformer and other listed components are critical and similar steps must be taken to ensure a successful project conclusion.

Within a week of operation, the operators had the diode rectifier up to 34.5 kA (108% of rated) and were eager to raise it higher. The transformers were running below the maximum rated temperatures and the transformer low-voltage bushing oil leak problems ceased.

Improved current balance, cooler transformer operation and nearly 8% extra output was achieved.

C. Case No. 3 - New Life for an Old Diode Rectifier using modern Digital Control

1) Background: One chlorine plant purchased two new 70 kA thyristor rectifiers, complete with transformers to replace obsolete equipment that could no longer be economically upgraded or repaired. They were connected in parallel with a 1970 vintage diode rectifier with a 100 kA rated output and an on-load tap-changer style transformer. The 100 kA rectifier was still in reasonable condition except for the controls. The control system was obsolete, difficult to troubleshoot and unreliable. In addition, power demand charges at the plant were significant so it was critical to control the maximum load precisely and run the plant at the highest possible load factor. These conditions pointed plant management toward upgrading the 100 kA rectifiers controls and tying the plant's three rectifiers together with an automatic power demand controller.

2) New Control System: A new PLC control system was installed to replace the 100 kA rectifier's electromechanical relay controls. The saturable reactor controls were replaced with electronic tracking power supplies. A PC based power demand controller was installed to automatically adjust the cell room current to maintain the plant power demand at the contracted amount they had agreed to take for the month.

3) Results: The life of the 100 kA rectifier was extended for another ten years. The PLC controls and tracking power supplies were very reliable. The plant demand controller paid for itself in two months.

D. Case No. 4 - New Life for Diode Rectifiers by Rebuilding the Transformer

1) Background: A chlorine plant operated four, 55 kA, parallel-connected diode rectifiers at 60 kA and more for twenty years. Each rectifier used 480 diodes, 12 oil-immersed saturable reactors and a 55-step on-load tap-changer. Overheating of the transformers was minimized by converting the transformer forced-oil, forced-water cooling system to a forced-oil, forced-air system with much greater cooling capacity. This was done early in the life of the plant and helped to keep transformer operating temperatures close to allowable levels. Nevertheless, continued operation at overload conditions created hot spots in the transformer windings and tap-changer contacts. Because, the plant had a regular transformer oil gas analysis program, they were able to detect most incipient faults in the transformer windings and tap-changers. After twenty years of operation, the increasing failure rate of the rectifier diodes caused the plant to replace them with newer, higher rated diodes that had an overall rating of 70 kA each and included air-cooled reactors. The rectifiers were pushed to about 62.5 kA each. As expected, the frequency of tap-changer repairs winding insulation degradation increased to a point where rectifier output could no longer be maintained at high levels. Transformer gas analysis coupled with failure frequency analysis indicated that the life of the winding insulation was no more than one or two years.

2) Transformer Upgrade: The plant's two options were:

a) Rewind the transformers and look for ways to reduce winding hot spots and increase the current rating of the tap changers;

b) Purchase new, higher rated transformers to match the rating of the diode rectifiers.

The rectifier transformers were carefully examined during a scheduled plant maintenance outage. Following some thermal modeling and testing of the windings and the tap-changer contacts, it was determined that a 70 kA rating could be obtained from the transformers if the following changes were made:

Tap-changer:

- Change the shape of the contacts to reduce the contact area and reduce the number of moving contacts by one-half;
- Increase the pressure on the contacts by installing new high-tension springs;
- Confirm the higher contact ratings by test.

Transformer windings:

- The low voltage winding was determined to be the limiting element and that both the cross-sectional area of the winding and the cooling duct size could be increased within the physical constraints of the transformer enclosure;
- Rearrange the location of the forced oil cooling ducts at the bottom of the transformer to ensure a more even flow of oil through the transformer windings;
- Install low-voltage winding temperature sensors to monitor and alarm over temperature conditions.

After obtaining firm cost estimates for buying new transformers or upgrading the existing units, it was apparent the upgrade option had a significantly lower cost.

3) Results: The rectifier transformers were rewound and upgraded over a two-year period. Total plant capacity was successfully increased to 280 kA. New life to four old rectifiers was obtained at very reasonable cost.

E. Case No. 5 - New Life for a Chlorine Plant by Rebuilding a Used Rectifier

1) Background: A chlorine plant had very high gas-in-oil test results on both of its two 60 kA diode rectifier transformers. Indications were that failure could occur in the next 6 to 18 months if load was not reduced or repairs made. At the same time, the plant also wished to increase production. Because of the short timeframe before failure could be expected, the plant first looked at the used equipment market for equipment that could quickly replace the ailing transformers. A used rectifier complete with a fairly new rectifier transformer with a 70 kA rated output was found. Unfortunately, the equipment had been out of service for over six years and was not protected from the weather. The transformer was in good condition but the diode rectifiers had not been heated or protected against rain.

2) Rectifier Rebuild: A detailed cost estimate showed that the installation of the used transformer together with a rebuilt rectifier was one-third the cost of a new unit. In addition to being able to provide more production, the unit could be rebuilt and installed in four months. The plant decided to proceed with the used transformer and rebuilt rectifier option after getting a firm price for the work.

The used rectifier and transformer came with spare parts, complete documentation including drawings, parts lists, operating and maintenance manuals and a complete operating history record. This was of great value in making the decision to rebuild the rectifier.

Because the rectifier was exposed to the weather for so long it was necessary to completely disassemble, clean and repaint everything, replace some defective parts, reassemble and test the unit.

3) Results: The transformer and rebuilt rectifier was completely rehabilitated, tested and shipped to the plant site in less than four months. The 60 kA unit was removed from service and replaced with the 70 kA unit in ten days. The rebuilt unit came into service with a minimum of effort and was online at rated load within a few hours. The 60 kA transformer was rewound so it could be available to replace the plant's second 60 kA unit.

V. Conclusion

The five examples of bringing new life to old rectifiers described in this paper show that chlorine plants have very cost-effective options available to address the problem of aging and overloaded rectifier equipment. It has been shown that the upgrade of old rectifiers, especially their control systems, provides some highly desirable features, including:

- PLCs and current monitoring increase output by up to 12%;
- Faster troubleshooting from vastly improved diagnostic capability;
- Higher control accuracy, which provides the opportunity to lower power demand costs;
- Elimination of obsolete and unsupported control components;
- Reduced power costs with automatic power demand control;
- Remote monitoring, control and communication capability from new digital controls reduces downtime and improves access to remote technical support.