

Adaptive VAR Compensation - A Real Solution to Reactive Power Problems

1.0 Introduction

The use of capacitors as a source of reactive power to compensate for the demand of inductive loads is well established and adopted worldwide. Conventional methods for switching these capacitors, however, can generate large transients that adversely affect sensitive loads. This power quality concern coupled with the inability of these conventional systems to accurately measure and compensate for the requirements of the load renders the conventional switching approach inadequate for applications involving loads with dynamic VAR requirements.

As deregulation transforms the electrical industry, reactive power management is more important than ever. Market forces in a deregulated environment are expected to force pricing structures such that customers with poor power factor will pay for their reactive load as well as their real power demand. Tolls associated with wheeling power will have to cover total power (kVA) since capacity and losses will derive from kVA and not just kW. Increasing power quality concerns associated with dynamic "problem loads" can also be expected to drive the need for effective solutions in the area of reactive power management.

2.0 The Basic Operating Principles of the Adaptive Var Compensator (AVC)

At the heart of the AVC, a microprocessor-based controller constantly monitors the phase voltages and the line or load currents, updating the switching pattern of the capacitors as required on a cycle-per-cycle basis. By measuring the peak magnitude of the current's inductive component (obtained as an instantaneous value at the zero crossing of the corresponding phase-to-neutral voltage waveform), the microprocessor-based controller determines the required capacitive compensation that must be connected to each phase in order to maintain the selected operating mode. The controller filters any harmonics that are present on the voltage or current reference waveforms to ensure that compensation is based on the 60-Hz or fundamental components only. An appropriate amount of reactive power is then injected into the system during the following cycle, giving a maximum response time of one cycle or 16.6 milliseconds for a 60-Hz power system. Reactive power compensation is performed on a phase-to-neutral basis; allowing phase independent control and operation ideally suited to meet the dynamic requirements of unbalanced systems. In addition, since the AVC monitors the load currents at the AVC node, it operates only when load currents are detected. Thus, over-voltage or self-excitation conditions are prevented.

This approach to reactive compensation ensures a quick response and maximum flexibility in the step-wise control of the reactive power flow through the supply system. Every capacitor is pre-charged to the peak of the supply voltage and remains charged until a triggering signal is applied to the solid state switch (SCR). The triggering signals are synchronized to set the switches into conducting mode only when the system voltage reaches its peak. At this instant (which corresponds to the natural zero crossing of the capacitor current), the potential across the solid state switch is near zero. Using this technique, no harmonics are generated and no switching transients are originated by the AVC operation. A variety of control algorithms are available depending on the type and nature of the load. The optimum algorithm and valve arrangement is determined based on the application, the reactive power profile of the load and the required response characteristics.

3.0 Main Components

The main power components within the AVC are capacitor elements, de-tuning reactors and solid-state valves (Figure 1).

by A. Jefferson,
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Over the past ten years, thyristor switched capacitor systems have proven their ability to deal with the reactive power management demands of dynamic loads. This article covers the basics of Adaptive VAR Compensation systems, focussing on a Trench pioneered technology.

Au cours de la dernière décennie, les systèmes de condensateurs commutés par thyristor ont démontré leur capacité à subvenir aux demandes des charges dynamiques en termes de pouvoir réactif. Cet article vous fournira les rudiments des systèmes de compensation adaptés en VAR, en se basant sur une technologie conçue par « Trench ».

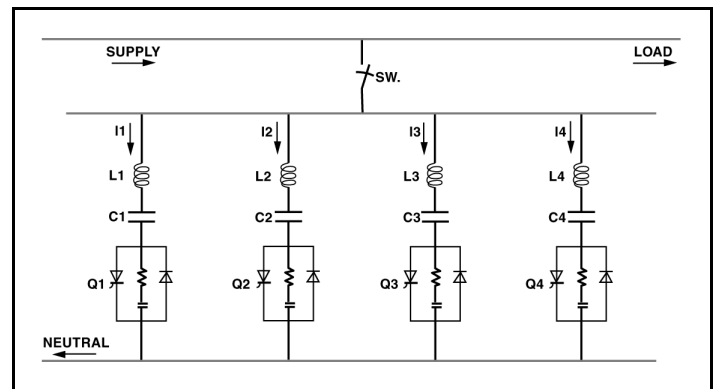


Figure 1: AVC Simplified One-line Diagram

The AVC's capacitive increments work in a stepwise fashion with a controlled design parameter referred to as 'resolution' (kVAR). Resolution is defined as the maximum reactive power that may be drawn from the supply system or injected back into the supply system when the AVC is operating within its rated kVAR limits. Resolution kVAR is equal to one half of the minimum stage (Q1).

The per-phase compensating reactive power, supplied by the AVC, is divided in several stages using binary increments; i.e., $Q1 \cdot (2^0, 2^1, 2^2, 2^3)$ for a four-stage AVC, where Q1 is the reactive power generated by the first capacitor stage. This number of stages and the value of Q1 are designed according to the requirements of the application. The total AVC reactive power is calculated as $3 \cdot Q1 \cdot (2^0 + 2^1 + 2^2 + 2^3)$. Each capacitor stage is fitted with a discharge resistor that dissipates the stored energy, reducing the voltage across the capacitor terminals to 50 Volts, one minute after disconnection.

Each capacitor stage is controlled by a set of solid-state valves (composed of one SCR and one diode connected in anti-parallel). The reverse-biased diode enables the capacitors in each stage to remain

charged to the peak value of the supply voltage and provides a path for the flow of the negative half cycle of the capacitor current. During energization, when the supply voltage crosses zero, the diodes conduct thereby charging the capacitors to the peak value of the supply voltage. At this instant, the AVC current changes direction and the diodes stop conducting. All capacitors become pre-charged and remain in that condition until a control signal is sent to the SCR's to set them in the conducting mode.

The AVC accomplishes reactive compensation with the harmonic filtering necessary for the existing operating environment. When required, each stage of the AVC is tuned appropriately using a series reactor, away from any potentially damaging resonant conditions.

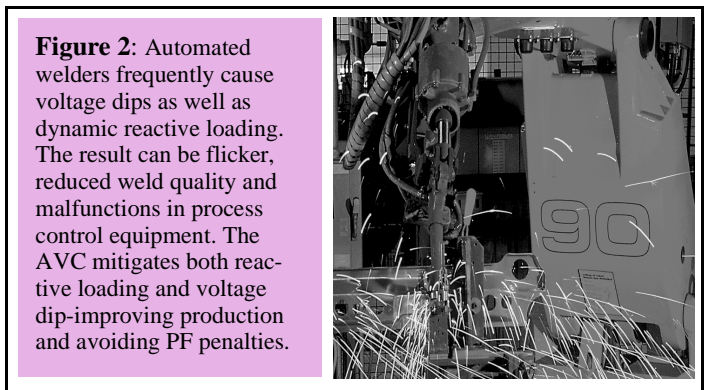
The in-service experience and benefits of the technology are investigated with three “real-life” case studies; in each of these applications the AVC technology has been successfully used to mitigate a specific significant power quality problem. The three applications are:

- a resistance welding application generating irritating voltage flicker,
- a marine terminal container ship cargo facility that faced huge billing penalties due to the dynamic nature of its VSD controlled cranes, and
- an extreme reactive power requirement of the new generation linear induction motor (LIM) powered roller coasters.

4.0 CASE 1 - Resistance Welding

4.1 The Problem

Resistance welding loads are amongst the most difficult loads to compensate. The problem example is a large industrial plant that employs two 350 kW automated 3-phase welders in the manufacture of wire shelving systems. Typical welding operation includes positioning shelf wires, clamping and welding (Figure 2). A chain system advances the shelf and the whole process recycles about once every second. The heat cycle of the weld is adjusted based on the type and size of material being welded. This can be adjusted by changing the tap connection on the welding transformer and by adjusting the thyristor firing circuit. Although each welding machine operates independently, measurements have confirmed that the machines often overlap and weld at the same time.



The welders are connected line-to-line at the 480 V bus and are fired concurrently for several electrical cycles (three to five cycles depending on the weld material). The duty interval ranges from approximately one to 10 seconds. The worst case reactive power demand occurs when the two welders “overlap” in operation. Since the power rating of the welders represents a major portion of the total power demand, the bus voltage experiences substantial and repetitive voltage dips (Figure 2). At the high voltage, or Point of Common Coupling (PCC), the utility

* Basically, the P_{ST} is a European developed statistical measure of flicker intensity as outlined in IEC 61000-4-15.

serves other customers who complain about voltage flicker.

Although the mitigation of voltage flicker was the prime focus for this particular application, weld process quality was also a key consideration. The repetitive voltage dips were also believed to be compromising the weld quality and contributing to an increase in related welder maintenance costs.

4.2 The Solution

To address the dynamic requirements of the load a 980 kVAR, 480 V AVC was installed on the secondary of the main transformer at the 480V bus (Figure 3). The AVC was sized to compensate for the welder “overlap” condition, supplying the reactive power demanded by the welders and thereby mitigating the voltage flicker on the supply system.

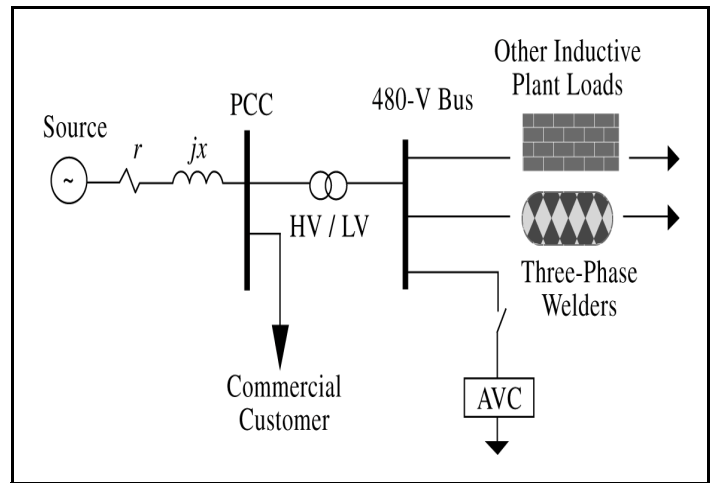


Figure 3: Simplified One-Line Diagram

The AVC has been operational since March 1995 and the flicker complaints have stopped. With the AVC in place, tests indicate that the maximum voltage drop has been reduced from 13.5% to 1.8% on a 480V base and the flicker intensity has been limited to a P_{ST} * level below 1.0 at the utility PCC (Table 1).

Table 1: Flicker severity at the point of common coupling

| Flicker Severity in (P_{ST}) p.u. | Phase A at PCC | Phase B at PCC | Phase C at PCC |
|---------------------------------------|----------------|----------------|----------------|
| No AVC | 1.132 | 1.113 | 1.132 |
| With AVC | 0.897 | 0.667 | 0.768 |

5.0 CASE 2 - Seagirt Marine Terminal

5.1 Problem

The Seagirt Marine Terminal is a modern container ship cargo facility that opened in 1990. Supplied by two 13.2 kV feeders with cross-tie capability, the terminal employs seven rail-mobile cranes to on-load and off-load container ships calling at the Port of Baltimore for transfer to and from rail and trucking connections. These cranes utilize variable speed silicon controlled rectifier (SCR) direct current (DC) drives to power the DC crane motors. Because the seven cranes easily constitute the terminal's largest electrical loads, the use of SCR DC drives causes an extremely poor facility power factor, often times less than 40%. In addition, the start and stop working cycle of the cranes causes rapidly

fluctuating power conditions, complicating efforts to correct the poor power factor. Heavy distortion caused by the SCR drives also produces significant harmonic currents during high demand periods.

As a 13.2 kV supply voltage customer, a significant portion of the Seagirt Terminal's monthly electric bill is based on the highest 15 minute averaged demands measured during on peak and off peak times. Seagirt's demand is billed as the greater of the peak kW or 90% of the peak measured kVA. Any power factor less than 90% would therefore result in additional demand charges for the terminal. For billing purposes, worst case reactive load conditions of 4462 kVA, 1772 kW, and 39.7% power factor had been observed. Poorer power factors at lower load conditions were not uncommon.

5.2 Solution

To meet this challenge, BGE teamed with Trench to design and install an AVC power factor correction system at the terminal (Figure 4). Using AVC technology, cycle-by-cycle compensation could be accomplished, enabling the power factor correction system to keep up with the dynamic nature of the crane loads, including regenerative transients caused by crane hoist lifting and lowering operations. In addition to its dynamic response, the AVC accomplished reactive load compensation without injecting additional transients and provided the harmonic filtering necessary for the existing operating environment.



Figure 4: This partnered AVC installation is saving the Seagirt Marine Terminal in Baltimore roughly \$220,000 US annually in demand and PF charges, and at the same time freeing distribution capacity for its utility Baltimore Gas & Electric. (Seen in the photo is Ed Wilson, Project Engineer with Constellation Energy Source, a premium power group of BGE).

To build the necessary reactive power management system, two 2400 kVAR units were installed. Since the two incoming BGE feeders each fed essentially half of the terminal loads, the two AVCs were connected via 13.2kV/600V transformers on opposite sides of the cross-tie between the billing metering cabinets and the outgoing site distribution feeders. They operate as separate compensating systems but because they use downstream parameters for AVC control, they can operate in parallel during closed tie supply conditions.

The AVCs were installed at Seagirt Marine Terminal in January 1997. The project is a resounding success with savings to the customer in excess of \$200,000 US annually. A sample of measurement data (compensated versus uncompensated) shows the effect of the AVC's dynamic compensation (Figure 5).

6.0 CASE 3 - Six Flags America

6.1 Problem

The new generations of roller coasters rely on Linear Induction Motor (LIM) launch systems to achieve faster and more thrilling speeds. A conventional roller coaster train is hauled slowly to the top of a hill by a chain lift so that the vehicle gains potential energy. Once over the brow

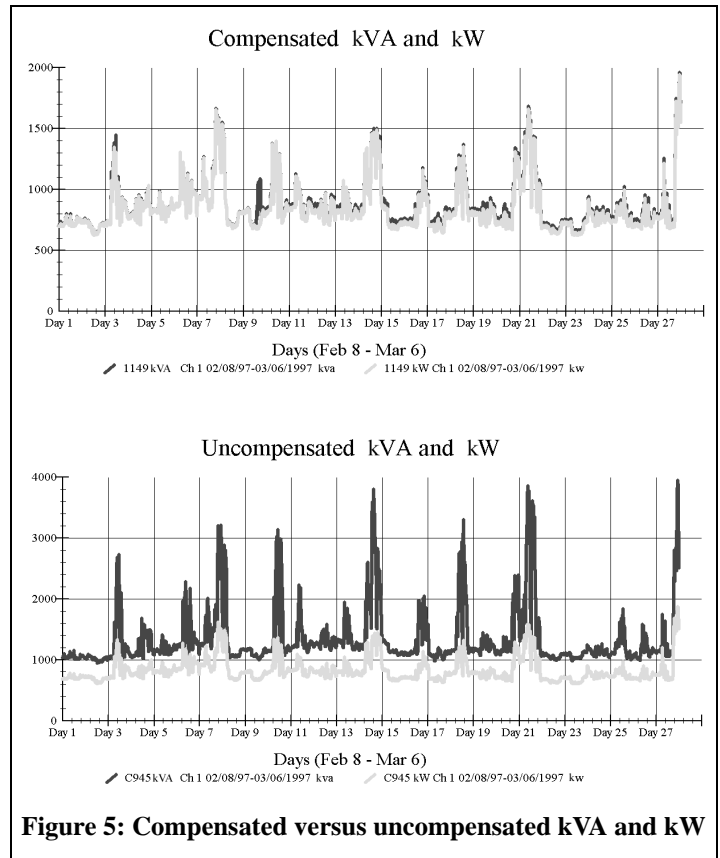


Figure 5: Compensated versus uncompensated kVA and kW

of the hill, the vehicle relies on gravity to accelerate the passenger car. In an attempt to reach higher speeds (without having to build higher hills) other alternative launch systems have been developed; however LIM launch systems are simpler and offer significant advantages in coaster control. The real flexibility of the LIM approach lies in the fact that LIMs can generate force without contact, making the addition of more boost or brake feasible throughout the course of the ride.

Six Flags America, an amusement park in Largo, Maryland, installed a new LIM controlled roller coaster, "The Joker's Jinx"™. This application (Figure 6) uses 43 LIM pairs installed along a 200-foot horizontal track. The passenger vehicles carry lightweight aluminum fins acting as motor reaction plates and the resulting acceleration is a whopping 60 miles per hour, from a complete stop, in just over three seconds.



Figure 6: AVCs provide the extra reactive power needed by the new generation of LIM amusement rides such as at this Six Flags installation.

All this excitement comes at a cost to the electrical supply system since the predicted peak kW and kVAR demand is 3500 kW and 4100 kVAR respectively, with average demand of 2400 kW and 2800 kVAR over a period of just 3.77 seconds. Without dynamic reactive compensation, excessive voltage drops will adversely impact ride performance and exceed the utility flicker criteria for adjacent customers.

Furthermore, the performance characteristics of the LIMs will require a minimum of 480 V at the motor terminals during operation for adequate thrust to be developed. Since power can be expressed as $P=V^2/R$,

the power output of the LIMs is proportional to the voltage squared. With this in mind, a 10% reduction in voltage results in a power decrease to 81% of nominal. Failure to develop adequate thrust will result in inadequate car speed and "saddling" whereby customers are stranded at a low point in the ride unable to clear the next incline.

6.2 Solution

Trench teamed up with Constellation Energy Source to meet this challenge by installing a 4100 kVAR, 520 V AVC to compensate for the reactive demands of the ride and an additional 2400 kVAR AVC (as a separate service) to provide the necessary transient voltage support on the BGE feeder.

The 4100 kVAR "ride" AVC was installed on the secondary of the BGE supply transformer and sized based on a predicted peak reactive power demand that was supplied by the ride manufacturer. The 2400 kVAR "feeder" AVC was sized to dynamically support the feeder voltage and offset a portion of the active drop along the BGE feeder. Both units work in tandem to support the ride voltage and mitigate the voltage flicker.

The AVC units were installed in April of this year and have again demonstrated their capability. Adequate voltage support was maintained for the LIM ride to operate successfully and the worry of irritating voltage flicker has been mitigated. As a side note, the impact on flicker was confirmed in a direct empirical manner. During the very first day of LIM testing, both AVCs had not yet been fully placed in service. Several complaints of flicker were received from the nearby neighborhoods. By the end of the first day however, both AVCs were in service and no more voltage complaints were received.

This achievement was heightened by the fact that the actual peak reactive demand of the ride turned out to be significantly greater than the 4100 kVAR that had been predicted by the ride manufacturer. In fact, the peak reactive power demand was more like 5300 kVAR. Consequently the maximum voltage drop was slightly larger than anticipated for one cycle. Even considering this last minute hurdle the average deviation during the launch is less than 2%, preventing observable flicker for the nearby utility customers.

7.0 Conclusion

These three cases are a sampling of applications within the electrical distribution market that have benefited from dynamic reactive compensation. Indeed, some of these market segments have standardized on an Adaptive VAR Compensation (Figure 7) approach to maintain optimum levels of performance and power quality. With over 50 applications in North America, the AVC technology has proven itself as a reliable and cost effective solution to "VAR" related power quality problems.

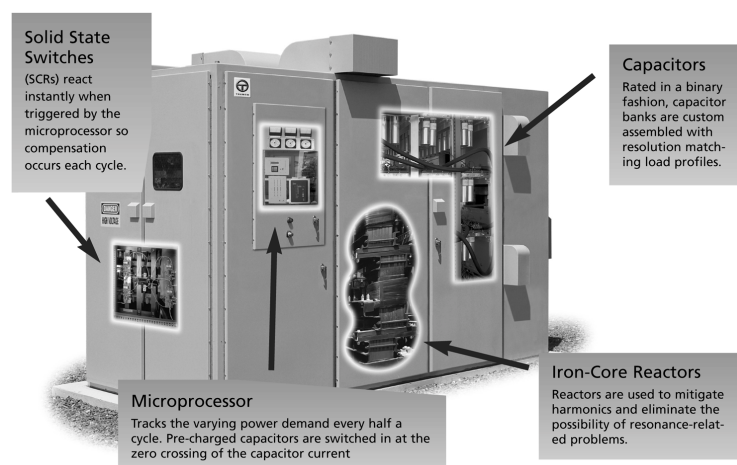


Figure 7: Cutout view of the AVC technology

8.0 For further reading

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- [4]. L. Conrad, J. Jatskevich, O. Wasynczu. "A Method for Evaluating Flicker-Reduction Strategies in Power Systems", IEEE Transactions on Power Delivery Publication PE-310-PWRD-0-1-1998, January 16, 1998.

About the Author

Tony Jefferson has a diploma in Electrical Engineering Technology (George Brown) and a Graduate Diploma in Management (Athabasca University). He is a certified engineering technologist in the province of Ontario and is currently completing an Executive MBA.



With over 12 years of experience in the electrical power industry, Tony has been involved in a variety of applications engineering, power quality, product management and marketing roles. Tony is a Sales/Marketing Manager for the Power Quality Products division of Trench Limited where he is responsible for a family of power quality solutions that includes the Adaptive Var Compensator.

Tony likes to spend as much time as possible with his wife and three young children at their home in Markham, Ontario. In his spare time, Tony enjoys reading, gardening, camping and fishing. He has been an associate member of the IEEE since 1990.

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