Active Voltage Correction for Industrial Plants

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***Abstract*—Electric power supply voltage disturbances and, in particular, voltage sags, have been clearly identified as major problems to sophisticated continuous-process-based industries. Electricity network operators are often not able to provide the level of quality demanded by these industries at an economically viable cost using traditional distribution network reinforcement techniques. In recent times, considerable effort has been expended in the identification, quantification, and mitigation of voltage disturbances. Recent power electronic advancements have allowed the development of a new range of high-performance power conditioning equipment that can mitigate problems with the incoming power supply at the point of interface with the utility or within the plant internal electrical distribution system.**

This paper reviews the technologies available to perform high-speed voltage correction and discusses the results of practical application.

***Index Terms*—Flicker, harmonics, mitigation equipment, transient overvoltages, voltage sags.**

I. INTRODUCTION

POWER QUALITY problems are becoming an increasingly major concern for industrial electricity consumers. Modern electronic equipment is much more sensitive to sags and other voltage disturbances than traditional electromechanical loads. Many modern loads, such as most personal computers, adjustable-speed drives, dc motor drives, and industrial rectifiers, appear as nonlinear loads on the incoming supply. The current loading of these nonlinear loads is often very distorted due to high levels of harmonics. This, in turn, creates harmonic voltage distortion problems in the plant electrical system. Power quality problems in industrial environments have been the subject of a large number of previous technical papers and studies [1]–[3].

Faults in the electrical distribution system can cause localized outages as well as widespread voltage sags which spread out through the distribution network, affecting large numbers of customers. Voltage sag lasting only a fraction of a second can cause considerable production and quality losses for many continuous process applications such as found in the petrochemical processing industry. Research has shown that power quality is a serious issue, costing North American industries billions of dollars in lost revenue each year [4].

Recent advances in power electronic inverters and powerful 32-bit microprocessors have allowed the development of advanced series medium- to high-power voltage conditioning systems. These systems allow protection of industrial plants from voltage disturbances and the mitigation of harmonic problems. It is now possible to provide near instantaneous voltage correction of commonly occurring voltage disturbances such as sags, surges, harmonic distortion, and flicker through the use of advanced inverter-based regulation techniques.

The new inverter-based conditioning solutions are gaining wide market acceptance. They have proven to be reliable and of financial benefit to potential industrial customers. Businesses require a financial justification before management approval is given for the introduction of relatively costly new technologies. Quantification of financial paybacks from new technology power conditioning equipment can be difficult, and this is slowing the market acceptance of the various new products available. A financial payback can be calculated if site power quality history is available, site equipment sensitivity to power abnormalities is known, and a historical record has been kept of disturbances experienced due to power quality problems including their direct and indirect costs.

The benefits of voltage disturbance conditioning devices are the savings in production and business losses that would have been incurred had the equipment not been installed.

II. VOLTAGE DISTURBANCE PROBLEMS

Voltage disturbance problems that can be typically found on plant electrical supplies are as follows:

- surges;
- sags;
- transient overvoltages;
- harmonic voltage distortion;
- flicker.

All of the above problems can impact plant performance. Overvoltage conditions such as surges and transients can result in insulation breakdown of connected equipment or failure of voltage-sensitive devices such as diode rectifiers. Harmonic voltage distortion can result in equipment damage by inducing harmonic currents in connected loads such as motors and power factor correction capacitors. Flicker in the plant supply voltage can result in operator eyestrain in extreme situations.

It is generally accepted that sags are normally the most costly voltage disturbance problem. Voltage sags of sufficient magnitude to impact plant performance typically occur ten times more often than supply outages. The remaining voltage present during these sags will seldom drop below 70% of the nominal supply

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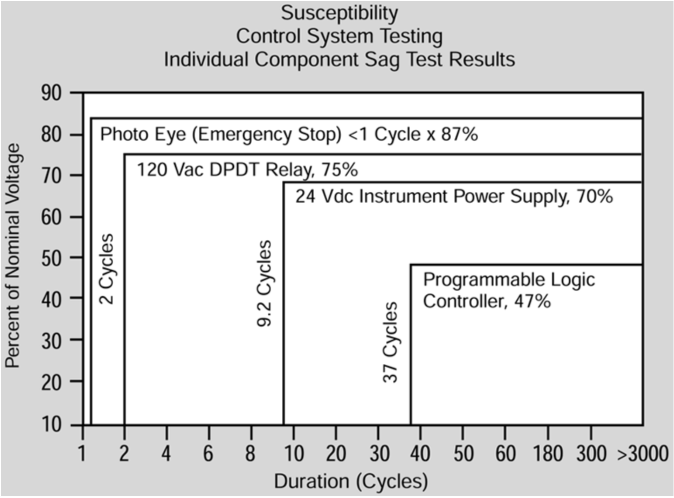


Fig. 1. Susceptibility of various plant loads to voltage sag events.

voltage level, but this is normally low enough to cause malfunction of sensitive connected equipment such as programmable logic controllers (PLCs), computers, sensitive transducers, relays, contactors, and some discharge lighting systems. The susceptibility of various types of connected industrial plant loads to problems resulting from voltage sags are shown in Fig. 1 [5].

The causes of voltage sags can be divided into two main categories:

1) utility transmission and distribution network generated events;
2) in-plant local problems typically caused by the starting of large electrical load such as three-phase motors.

Although local problems can be quite common, they tend to be predictable by nature, so steps are normally taken to overcome them. Solutions include the separation of problem loads onto their own supplies and the application of soft starters and adjustable-speed drives onto problem motors in an attempt to reduce starting current magnitudes.

Far more insidious problems are the voltage sags that enter the plant electrical environment through the utility connection. They tend to be less predictable, as they normally result from disturbances in the electrical supply network. The utility can often reduce the incidence of sag occurrences by improving maintenance procedures but in many cases significant improvements can only be made following large capital investment in the transmission and distribution infrastructure.

Continuous process industries are most susceptible to voltage sags causing equipment malfunctions or trips that result in plant down time, product loss, and other intangible costs.

III. POWER QUALITY MEASUREMENT

There has been considerable recent effort applied to the development of standards defining how particular power quality events should be named, recorded, and quantified. One such standard is IEEE 1159 [6], which provides a good basis for event definition and is starting to be adopted by manufacturers of power quality measurement equipment.

Power disturbance analyzers can accumulate very large volumes of data that sometimes can be hard to transfer, manipulate, and store. Significant effort has been applied to data compression techniques on the measurement instruments themselves. Data compression when combined with presorting and discarding of less significant test data can greatly reduce the amount of data, making the use of telephone modems for data transfer practical and cost effective. New three-phase voltage disturbance monitoring instruments are available at reasonable costs that allow profiling voltage supply quality over extended periods of time. Meters can be configured to allow remote monitoring of site power quality information, as shown in Fig. 2.

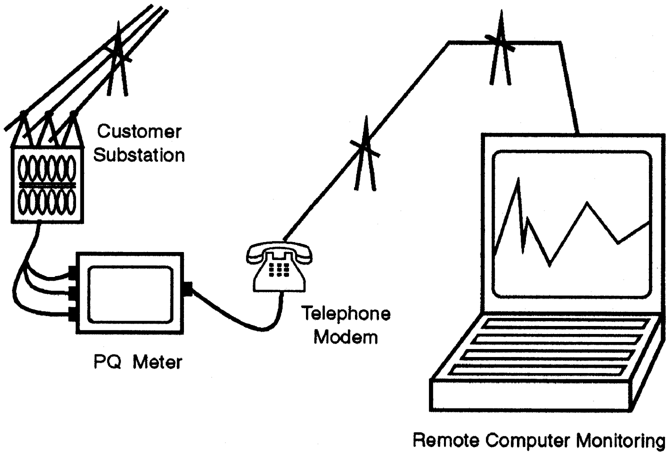


Fig. 2. Data acquisition system suitable for collection of voltage disturbance data.

Many power companies are now establishing networks of power quality monitors to gather information on network disturbances and the quality of supply at their customer's point of connection. Once data have been captured they must be stored in a database system capable of manipulating large quantities of time-related data. Clear and concise reports must also be available to allow presentation of power disturbance information in a format that is easy to interpret by power company personnel and customers. Graphical presentation of data can greatly simplify interpretation and analysis using various formats from the Information Technology Industry Council (ITIC), formerly the Computer Business Equipment Manufacturer's Association (CBEMA,) graph to three-dimensional histograms. Field data presentations such as shown in Fig. 3 can be very useful in assessing a site's suitability to the installation of modern inverter-based power conditioning.

IV. TRADITIONAL INDUSTRIAL VOLTAGE CONDITIONERS

Traditional voltage conditioning technologies used to protect sensitive plant loads are as follows:

- ferro-resonant;
- servo-variac;
- silicon-controlled rectifier (SCR) tap change.

Ferro-resonant conditioners use a saturable transformer and tuned capacitor to regulate the supply to sensitive loads. They can provide good protection for single load and good rejection of the plant-supply-born electrical noise. Due to their high transient impedance and relatively low efficiency, they are not well

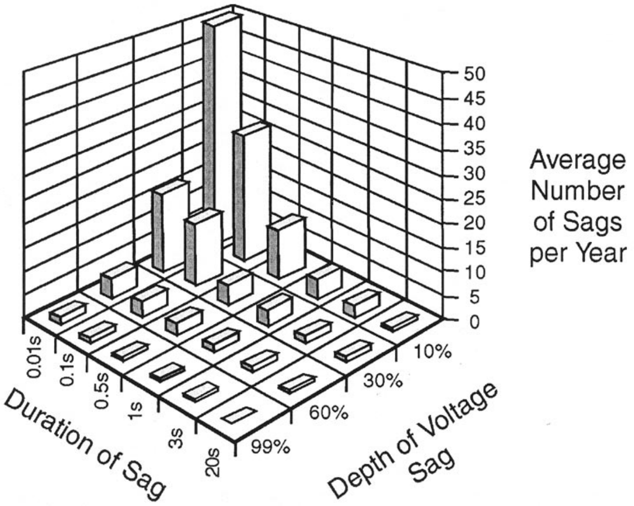


Fig. 3. Three-dimensional histogram representations of voltage sags experienced in a sample site per year, which exceed a range of depths and durations. For example, this site experiences up to ten voltage sag events a year of duration 0.01–0.1 s and depth of sag up to 30%.

suited to the protection of large sections of sensitive industrial plant.

Both single- and three-phase servo-variac voltage regulators have been available for many years. These electromechanical devices use high-speed servo motors to control variacs which inject correction voltage using a series-connected transformer to regulate the supply to sensitive plant loads. Servo-variac conditioners are available in ratings up to many megavoltamperes and operate with very high electrical efficiency, typically exceeding 99%. Unfortunately, response speeds of even the fastest servo-variac regulator designs is typically 750 ms–1.5 s, which makes them too sluggish to protect most sensitive plant loads. There are also maintenance issues due to the electromechanical nature of these devices with many moving parts and contacts.

Another commonly used voltage conditioning technology utilizes SCR tap-change technology. Like the servo-variac devices, the SCR tap-change conditioners use a series-connected transformer to correct for supply voltage variations. The actual correction voltage is derived from a tap-changed autotransformer arrangement using solid-state SCR switches. Electrical efficiency is similar to the servo-variac products and maintenance issues are greatly reduced, but, unfortunately, their output is not continuously variable. This makes them unsuitable for use in many larger scale protection applications where step voltage changes on direct-line-connected motors and lighting systems are not acceptable.

V. MODERN HIGH-POWER INVERTER-BASED VOLTAGE CONDITIONERS

Various modern inverter-based power conditioning products have been recently introduced to mitigate sag problems. One such technology recently developed utilizes the latest three-phase insulated gate bipolar transistor (IGBT) semiconductor technology with 32-bit reduced instruction set computer (RISC) microprocessor control. This technology has also been widely used in the design of modern adjustable-speed drives which makes it relatively low cost and commonly available. Ratings are available up to 6-MVA capacity with a range of maximum voltage correction capabilities and operating supply voltages.

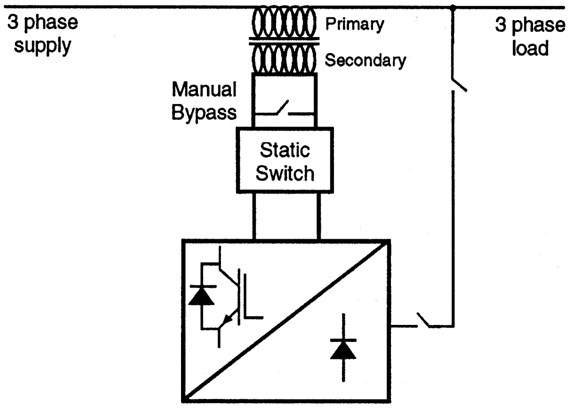


Fig. 4. AVC circuit schematic.

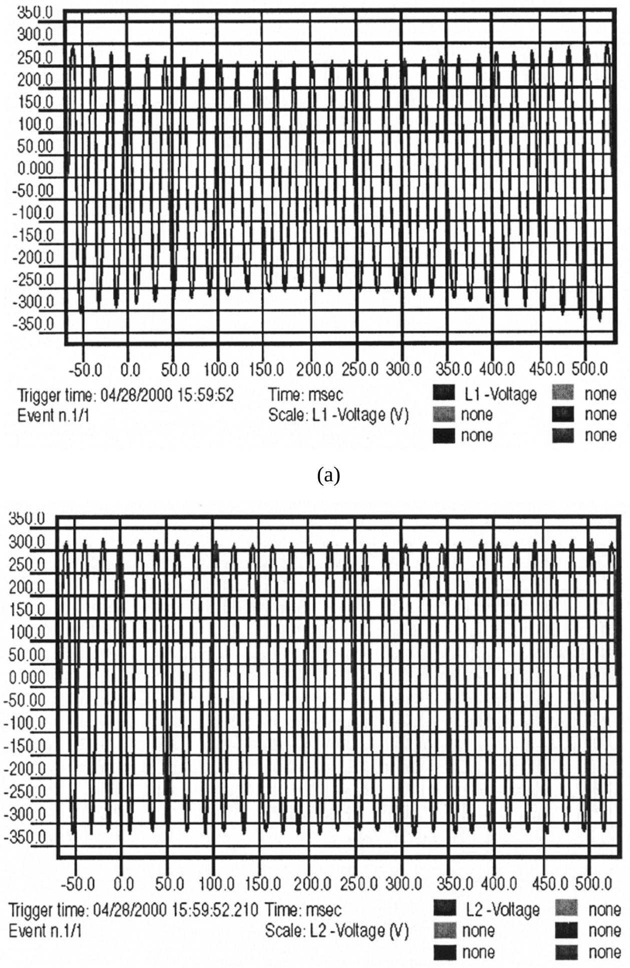
Such technology permits regulation of the plant voltage to within 2% of nominal value with a response time of 2–4 ms (depending on sag depth). The circuit schematic for the device is shown in Fig. 4. The microprocessor of the active voltage conditioner (AVC) continuously monitors each phase of the incoming supply independently. In the event of a sag or overvoltage on any one or all of the input phases, the AVC will determine the change to the voltage vectors and will then calculate the level of voltage correction necessary to bring the voltage waveform back to a regulated and balanced sinusoid. The injection transformer in series with the load is configured as a voltage source. In the event of a sag, the inverter will inject the additive voltage to the phase or phases that need the voltage boost through the transformer, resulting in a regulated output to the load.

Pulsewidth-modulated (PWM) switching waveforms are calculated by the microprocessor to control the IGBT switching devices. The inverter output voltage is then filtered before being injected back into the supply using a series-connected power transformer. Although the inverter dc-bus capacitors store a small amount of energy while the low voltage or sag is present, power for the inverter is obtained via a rectifier from the remaining plant supply.

Circuit simulation and practical application have shown that energy can be obtained from the utility network during the time of the sag disturbance with negligible impact on the remaining plant supply voltage.

The oscilloscope traces of Fig. 5(a) and (b) show typical supply sag and the AVC-corrected load supply, respectively. The trace shows correction for 20% voltage sag.

The performance provided by this new breed of inverter-based power conditioners would only otherwise be achieved with the near ultimate protection of an online uninterruptible power supply (UPS). Unfortunately, UPSs are not practical for many large-scale power protection applications because of their relatively large size, high cost, and low electrical efficiency. The AVC achieves its performance with superior efficiency and cost effectiveness, when compared with the UPS, because its power electronics need only be rated for



(a)

(b)

Fig. 5. (a) Plant supply (L1) undergoing voltage sag to 80% remaining voltage for 350 ms. (b) Corrected load voltage (L2) as measured on the AVC output.

the level of regulation being provided. The cost of a 1-MVA 20% voltage correction rated AVC is typically less than 20% of an equivalently rated UPS having 5-min battery backup. The AVC is not intended to provide momentary or prolonged outage protection such as that provided by UPS systems, because the UPS uses energy storage elements.

The AVC technology, as an added benefit, offers high-frequency voltage control, which allows the unit to act as a buffer to protect the load from plant-side harmonic voltage distortion. The magnitude of the correction voltage is manipulated fast enough to allow compensation for the major low-order voltage harmonics present in the incoming supply. This also applies to subharmonics and flicker, which can be a major benefit in certain applications.

Fig. 6 shows the AVC response to typical "flat-topping" supply voltage distortion. The inverter adds in the necessary voltage to correct for this distortion, resulting in a regulated sinusoidal output voltage waveform. The conditioner is not a harmonic filter in the traditional sense; if any loads generate harmonic currents they will still flow back into the plant supply. However, if other loads have distorted the supply bus voltage, the AVC will correct its output voltage to improve the waveform to its load.

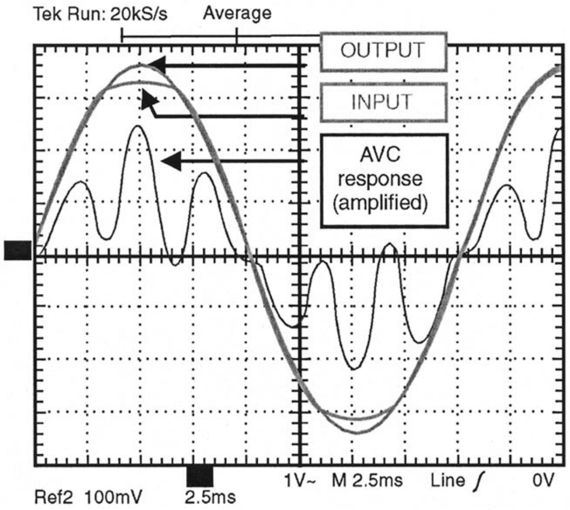


Fig. 6. AVC regulation of a "flat-topped" plant voltage waveform (INPUT). The AVC voltage correction response is amplified for clarity.

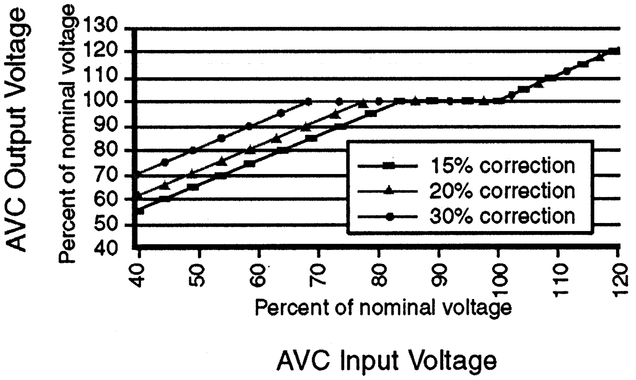


Fig. 7. AVC regulation characteristics.

AVCs have a capacity rating expressed in kVA and a voltage correction capacity expressed as a percentage. The AVC kVA capacity sizing is selected based on the load kVA rating plus a margin of over capacity in much the same way as a standard transformer. The percentage correction capacity is defined based on the sensitivity of the load and the likely magnitude of voltage sag events. For example, if supply sag events were commonly present on the plant supply with maximum remaining voltage levels of 70% and connected equipment had a tolerance to supply reductions of -10% maximum, an AVC with a correction capability of 20% or greater would be suitable. If a 20% correction AVC was selected and the incoming voltage drops to 70% nominal, the AVC would add in 20% voltage and the protected plant voltage would be limited to 90% of nominal value. However, if a 30% correction system was selected instead, the plant would see negligible voltage reduction for the same sag event.

AVC models are typically available with correction capabilities of 15%, 20%, and 30%, although special models with up to 50% capability are available to correct for particularly deep sag events. Fig. 7 shows the voltage regulating capabilities for various standard AVC correction options.

TABLE I
COMPARISON OF AVAILABLE VOLTAGE CONDITIONING TECHNOLOGIES FOR THE PLASTIC FACTORY PROTECTION APPLICATION

Feature/technology	Ferroresonant	SCR Tap Changer	Servo Variac	AVC
Continuously variable output voltage control	Yes	No, step changes	Yes	Yes
Response to transient load changes	Poor	Good	Good	Excellent
Response to supply voltage sags	Average	Good	Poor to Slow	Excellent
Efficiency	Poor	Good	Excellent	Excellent
Harmonic Voltage Correction	No	No	No	Yes
Peak output overloading	100-150%			1000%
Static Bypass	No	?	No	Standard
Manual Bypass	No	?	No	Standard
Fault Monitoring	No	No	No	Standard
Supply voltage event monitoring	No	No	No	Standard

The AVC's three-phase inverter is independently controlled, which means phase voltages can be independently adjusted. This allows the correction of plant voltage imbalance which can be particularly useful in protecting three-phase direct-online-connected induction motors which are particularly sensitive to this type of problem.

The AVC can also correct for supply low-voltage problems on a continuous basis. AVC configuration options are also available that allow correction of overvoltages and surges for applications where this is important. The standard conditioner design employs an uncontrolled diode rectifier to supply power to the inverter, which is unidirectional in power flow by nature. This does not allow correction of overvoltages; as for positive power loads, the inverter must remove energy using the series connection transformer. This energy cannot be returned to the supply through the diode rectifier. By replacing the diode rectifier with a bidirectional IGBT-based switching rectifier, this limitation is overcome. An alternative transformer-based configuration has also recently become available that allows correction of up to 10% overvoltage. Application experience to date has shown that overvoltage correction is required in very few applications.

VI. SITE APPLICATION OF THE AVC

An industrial manufacturer of mutlilayer plastic bags based in Auckland, New Zealand, was experiencing significant problems with plastic bag extruders during utility-induced voltage sags. Due to the high cost of plant upsets caused by voltage sags events, various voltage conditioning technologies were evaluated to establish the most suitable solution. Table I summarizes the relative strengths and weaknesses of the technologies available. A modern AVC was identified as the most suitable technology in this application.

Various measurements have been recorded for the 300-kVA AVC performance using a power disturbance analyzer. A typical result showing the AVC response to voltage sag is presented in Fig. 8.

Case Study 1: A 300-kVA unit of AVC with 30% sag correction capability was installed on one of the seven production lines in December 1997. The conditioner operated reliably for the 12-month duration of the trial. The benefit of the system became apparent in times of stormy weather when distribution faults in the overhead lines feeding the plant caused regular voltage sags on the plant supply. Practical proof of effectiveness was demonstrated when the AVC-protected line continued to operate even after all six nonprotected production lines had faulted and tripped following numerous sag events.

Case Study 2: In December 1998, the plastics manufacturer moved to new premises and, as part of the upgrading, purchased a 1-MVA-rated 400-V three-phase AVC with 20% sag correc-

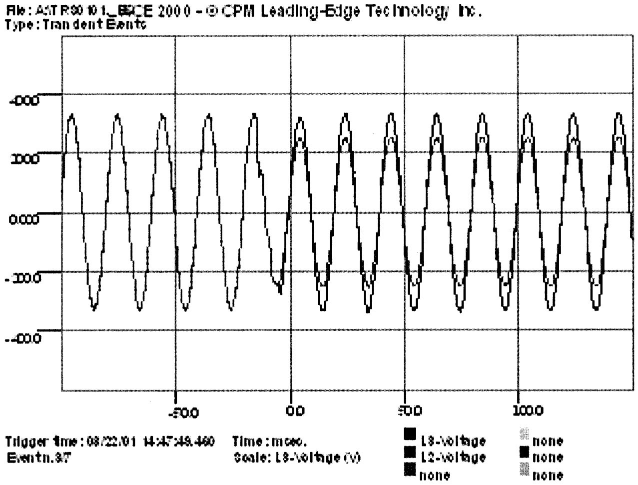


Fig. 8. Input (L2) and output (L1) voltage waveforms measured on a 300-kVA 30% correction AVC. The input line voltage is reduced from nominal 400 V to 310 V.

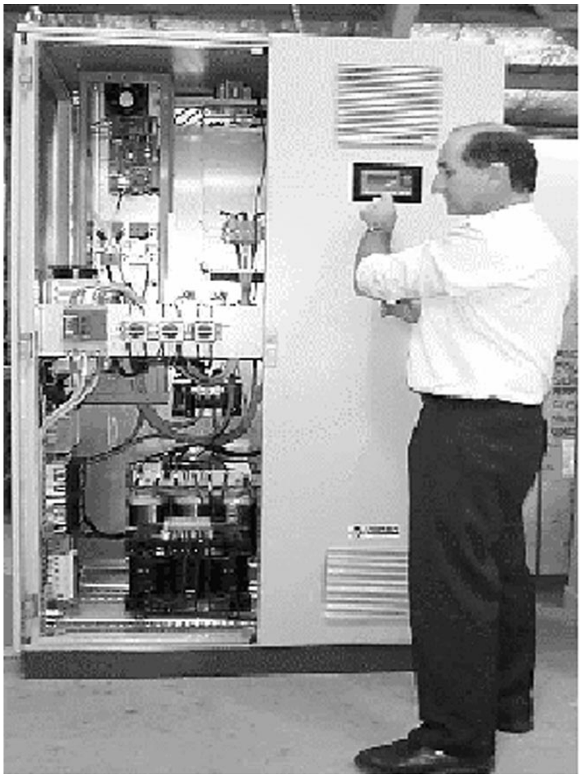


Fig. 9. 1-MVA AVC unit.

tion capability to supply their complete plant. The new device was commissioned in January 1999.

Power quality history has also been recorded using the powerful 32-bit microprocessor on the conditioner itself and is presented on the liquid crystal display of the device. Although the exact costs of power quality problems are difficult to quantify, in this application the plastics company clearly recovered the capital cost of the AVC equipment through savings in reduced product waste and increased plant run time.

The dimensions of this 1-MVA AVC unit are 1956 mm (77 in) high × 1016 mm (40 in) wide × 660 mm (26 in) deep (see Fig. 9). These dimensions exclude the transformer, which is installed adjacent to the remote switchgear. This AVC is air cooled with 99% efficiency.

VII. Conclusion

Recent advances in inverter and microprocessor technologies allowed the development of various new technology power conditioning and protection systems. It is now possible to economically provide effective single-point power correction for commonly occurring voltage disturbance problems and, in particular, voltage sags. These new active voltage conditioning technologies are likely to gain increasing market acceptance as plant sophistication increases and the costs of power quality disturbances are better understood by industry.

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Following a short teaching career, he joined Gulf Canada (now Petro Canada) in 1981 as a Central Engineering Specialist, providing technical support to the refineries in implementing capital projects and equipment selection. In 1995, he founded RPM Engineering Ltd., Mississauga, ON, Canada, a certified consulting company specializing in adjustable-speed drive applications, power quality studies, and power system analysis. He has been an invited speaker to several utilities in Canada.

Dr. Hanna is a Registered Professional Engineer in the Provinces of Ontario, Alberta, and British Columbia, Canada, and a Fellow of the Institution of Electrical Engineers, U.K. He is the Chair of the IEEE Toronto Section and was the Vice-Chair of the IEEE Petroleum and Chemical Industry Technical Conference that was held in September 2001 in Toronto, ON, Canada. He has authored 15 IEEE Petroleum and Chemical Industry Committee technical papers.

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He spent eight years in ac drive and power electronic inverter design, including the development of large IGBT inverters rated to 1 MW. In 1994, he co-founded Vectek Electronics Ltd., Napier, New Zealand, a manufacturer of large-scale inverter and power conditioning equipment, where he holds the position of Technical Director.