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FINAL REPORT

POWER FACTOR CORRECTION SYSTEM BY MEANS OF CONTINUOUS MODULATION

SUBMITTED TO:

U.S. DEPARTMENT OF ENERGY

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Part I: Executive Summary

The novel power factor correction system described here is an improvement over existing ones because it reduces the VAR's with no switching transients, continuously; i.e., without the customary VAR-jumps that result from the usual capacitor-switchings.

Work on this concept was begun in the early 1980's by Mr. Frederick Rohatyn. The invention was granted a U. S. Patent (No. 4,672,298) in June 1987. Mr. Rohatyn continued his experiments for four years following issuance of the patent. During that time, he built several prototypes in order to develop a practical realization of his idea.

The invention was evaluated technically by the U.S. Department of Commerce, National Institute of Standards and Technology (NIST), resulting in very favorable recommendations.

Work on the project and grant applications stopped due to Mr. Rohatyn's illness and ultimately his death in early 1993. Since March 1993, the industrial partner (International Electronic Technology Corp.) has continued the development effort for a 100 kVAR power factor control system at its facility at the Polytechnic University.

The industrial partner has provided the computer-based feedback control system, variable auto transformers, servo-motors, capacitors, enclosure and simulated loads which have been integrated and installed in a Polytechnic University laboratory.

The technological evaluation written by Dr. Vilas Nene, Dr. Jacob Rabinov and Richard W. Bartholomew for NIST explains the importance of power factor correction, reviews the current state-of-the-art, and comments favorably on the potential this new technology offers.

The energy consumption of any load is measured in kilowatt-hours (kWh), and the utility bills the customer on the basis of this kWh consumption. If a customer operates an inductive load, the utility system must supply, in addition to the energy, an additional out-of-phase current component which does not contribute energy, but which results in the requirement for larger generators and transmission and distribution networks, and which causes additional losses in the system. The utility, then, prefers to have the inductive load compensated so as to eliminate the out-of-phase current component, i.e. to operate at unity power factor or as close to it as is economically feasible.

The lagging power factor of the load on utility systems is currently corrected by using banks of capacitors at appropriate locations in the system. The amount of correction provided is proportional to the reactive volt amperes (VAR's) of the capacitors. Because of the variability of the load, it has been the practice to use several capacitors and switch them individually or in groups to provide the necessary power factor correction. This practice has several major drawbacks that the present invention is designed to overcome.

In the invention, the compensating reactive power is generated by a linear capacitor. A transformer is connected in series with the capacitor. The voltage applied to the capacitor terminals can be varied from zero to a maximum level. This is done by supplying the primary winding of the series transformer from a variable auto-transformer. This feature permits continuous variation of the reactive power generated by the capacitor.

The basic concept of the present invention can be explained with the help of Fig. 1.

TR #1 is an auto-transformer that has two taps (sliding contacts): *a* and *b*; each can be moved along the entire length of the winding. These two taps are, however, always equidistant from the center of the winding. This way the voltage V_{ba} can be varied from V_L to $-V_L$ in a stepless, continuous fashion.

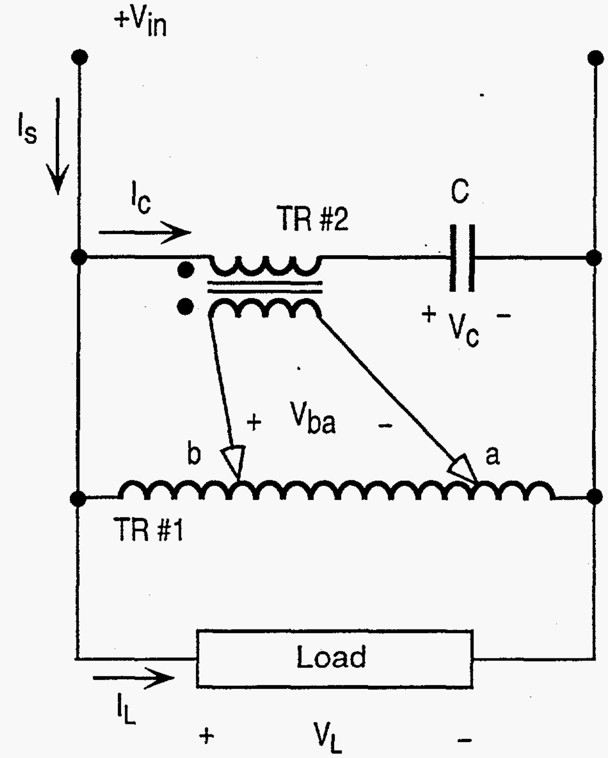


Fig. 1: Basic concept of the PF correction system

The capacitor C is connected in series with the secondary of transformer TR #2, whose primary winding is connected across taps a and b of transformer TR #1. For the sake of simplicity, the transformer winding ratio for the TR #2 is assumed here to be 1:1

Using the dot convection for the transformer winding as shown, one may write the following relationship between various phasor quantities:

$$V_L = V_c + V_{ba} \qquad \Rightarrow \qquad V_c = V_L - V_{ba}$$

the capacitor current is: $I_c = 2\pi\, 60 \cdot C \cdot V_c = 377 \cdot C \cdot \left(V_L - V_{ba}\right)$

and the input current is: $I_s = I_L + I_c$

As a result, the capacitor current I_c can be controlled simply by varying the voltage V_{ba} by moving taps a and b.

The capacitor $kVAR$ is given by:

$$kVAR = 0.377 \cdot C \cdot \left(V_L - V_{ba}\right)^2$$

Under ideal conditions in which losses can be ignored, the capacitor voltage can be controlled smoothly between zero and twice the line voltage and the kVAR's can be controlled similarly over a wide range.

Figure 2 presents a three-phase schematic diagram based on the configuration of Fig. 1. Each variable transformer feeds a primary winding of a 'series-transformer' having a turn ration of 87/66. Its secondary winding is connected in series with a secondary of a 'pre-boost transformer' that has a turn ratio of 69/92. This pre-boost auto-transformer permits adaptation of the system to a substantially higher capacitor voltage rating, and therefore, a reduction of the unnecessary bottom portion of the reactive power correction range; both of these measures have the purpose of cost reduction.

The novel device offers several potential advantages over the present practice of switching capacitor units. In spite of the additional transformer units required, the total cost of the system will be less than that of the system with switching capacitors. This is so because the cost of a single large high-voltage capacitor is lower than the cost of several small capacitors of equal total kVAR rating. When the series transformer has a turn ratio different than 1, then on the high voltage (sliding contact) side, the control current is smaller than the capacitor current. That tends to extend the life time of the mechanical contacts. Also, since the capacitor does not always operate at the rated voltage, the life of the capacitor is considerably increased.

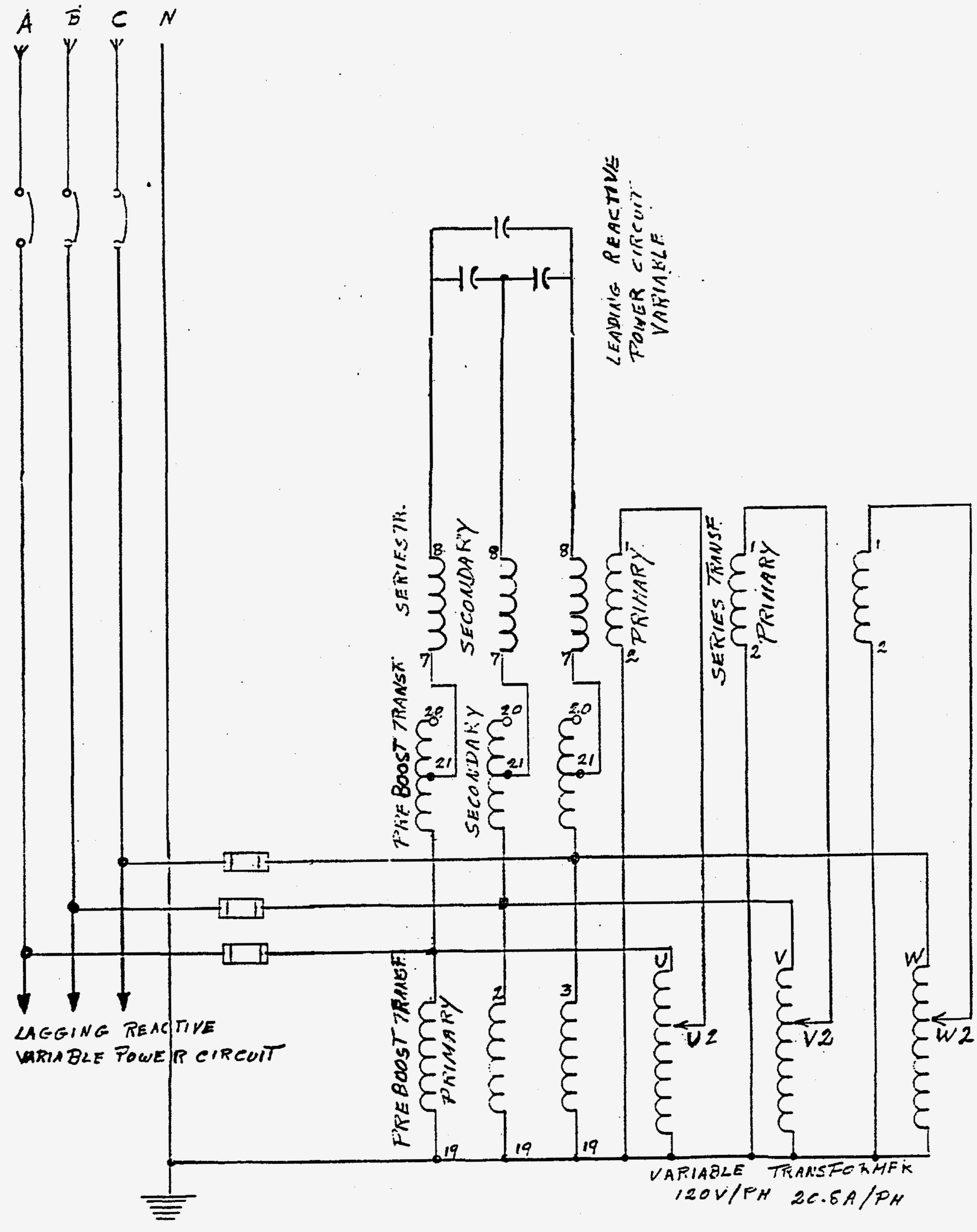


Fig. 2: Three-phase schematic diagram of the PF system.

This novel power factor correction method not only will be less expensive, but also will be attractive because of other features:

1. The secondaries (the series and the pre-boost) act as high-frequency rejection filters due to the leakage reactances of both transformers. This provides a measure of protection to the capacitor from high currents resulting from harmonic voltages. In addition, harmonic resonance with the reactance of the incoming transmission line is averted by this leakage reactance.
2. Switching transients are eliminated.
3. The system is mechanically and electrically robust.

Contractual obligations were satisfied by performing to completion the following tasks:

Task 1: The prototype was modified as necessary to perform as a 100 kVAR controller and to provide the ability to monitor pertinent operating parameters.

Task 2: The software for controlling and monitoring of the device functions was developed and configured.

Task 3: Tests of the prototype were carried out at the power laboratory of the Polytechnic.

Task 3a: The performance under balanced and unbalanced load conditions both with ganged and unganged auto-transformer control were evaluated.

Task 3b: The range and capacitor sizes needed for various loads and values of power factor were studied using the push-pull design of the auto-transformers.

Task 3c: The effect of harmonics on the unit using loads that generate harmonics were evaluated. Also evaluated for compatibility with the prototype was industry standard harmonic suppression circuitry.

Task 3d: Safety features evaluated were fusing, wiring, bypass switches and fault monitoring. Also evaluated were physical locks, secured or sealed cabinets, and password protection on programmable controls to insure that once fielded, no unauthorized changes could be made to the controller's software or to operational-service switches that could have adverse effects on site personnel.

Task 4: LILCO's assistance was requested in an effort to locate a small industrial or commercial user of energy with an unusually low power-factor.

Tasks 5: Accomplishments and goals reached during the first four tasks and sub-tasks prior to field demonstration were reported.

Task 6a: The Photocircuits plant in Glen Cove, Long Island, was selected for field testing because of the variety of different power factor loads.

Task 6b: The equipment was moved from the lab to the selected site.

Task 6c: Measuring methods similar to those used in the laboratory were employed. LILCO personnel were present as observers.

Task 7: The findings were analyzed in order to formulate recommendations for the improvement of the design.

Task 8: The present (final) report is herewith submitted.

Task 9: The findings of this project will be presented at appropriate technical and industrial meetings.

The prototype was tested at the field demonstration site with a motor load varying cyclically from a power of 138 kW with a power factor of 0.88 to a power of 32 kW with a power factor of 0.64. The cycling time was about 15 seconds. The prototype brought the power factor to unity within 6 seconds. The maximum power absorbed by the compensating unit was less than 6 kW or about 4%. The operating time could be reduced by increasing the torque of the servo-motor. The efficiency would be expected to improve with increase in the size of the power factor compensator and with increase in the voltage.

As for the market potential within the next 10 years, one may project a nationwide demand of 2500 to 6000 units of 100 kVAR each. The demand for export is anticipated to be much larger, based on less-than-unity-power-factor penalties imposed in foreign countries where energy costs are higher and generation capability more limited.

Based on the results of this study, the industrial partner intends to develop a line of production models and market them to power management companies worldwide.

Part II: Technical Description and Test Results

Schematic diagram:

A detailed description of the invention is contained in the Patent (see Appendix). A schematic diagram of the testing arrangement is shown in Fig. 3. The 150 HP motor was connected to the 480 V, 3-Φ main through a wall switch. The P.F. unit itself was connected to a wall connector located inside the motor housing through an auxiliary power switch. Current monitoring was provided with the aid of current transformers at a ratio of 400/5 A. Voltage monitoring was provided directly from line at 480 V.

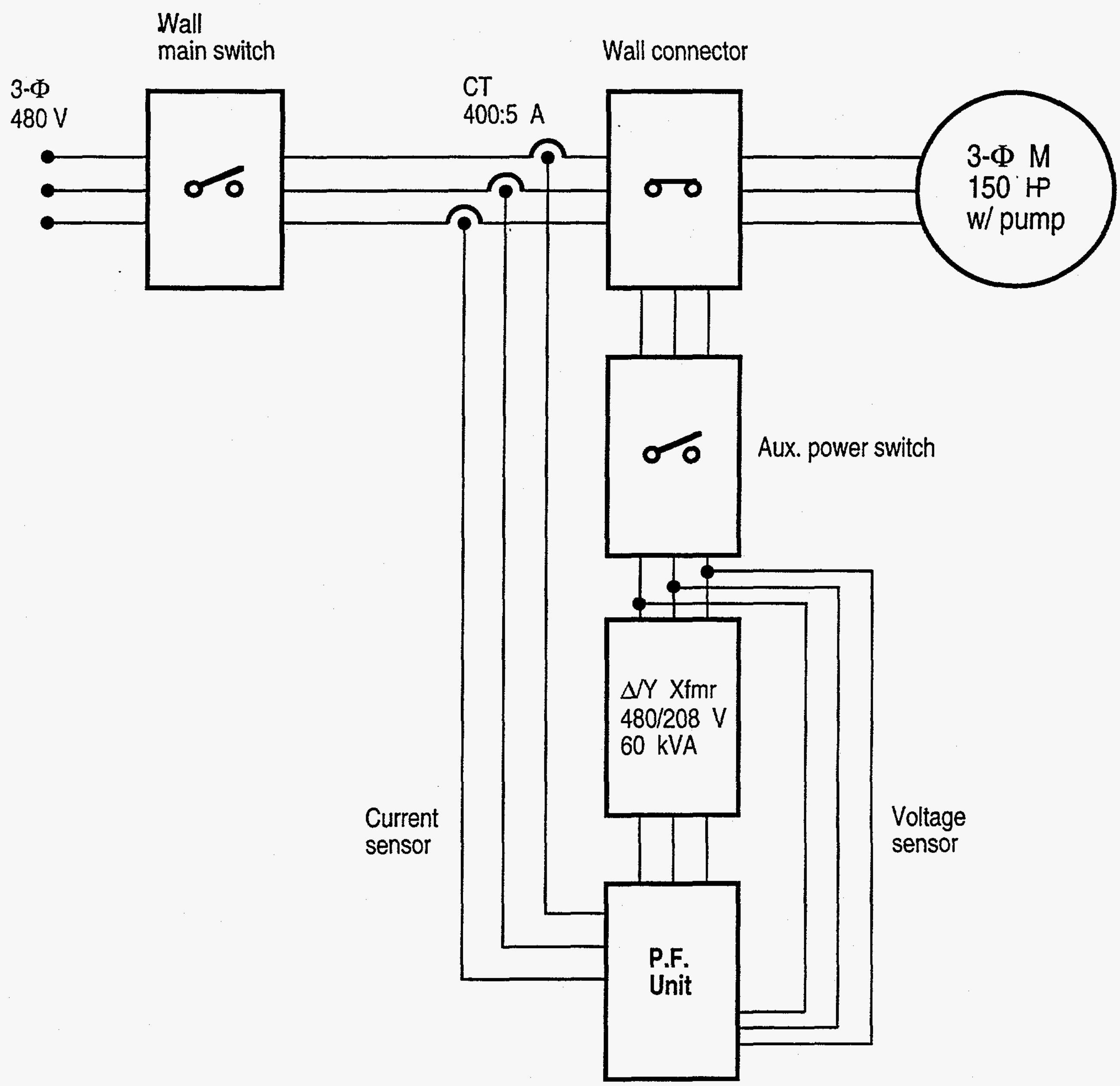


Fig. 3: Schematic diagram of the testing arrangement

The existing power factor correcting unit was designed for a line-to-line voltage of 208 V. The motor / compressor system selected for testing was supplied by a 480 V line-to-line source. Therefore, the Δ/Y step-down power transformer, 480/208 V 60 kVA, had to be used. This transformer would be eliminated by redesigning the unit for 480 V.

Figure 4 shows a detailed diagram of the complete prototype and the testing arrangement. Starting from the top left are the 480 V, 3-phase, 60 Hz supply line; the 150 hp motor/compressor load; and the power factor compensator, fed through a Δ/Y step-down transformer.

The three current transformers and the three phase voltage sensors feed three transducers whose outputs, dependent on the VAR's/phase, are the input signals to the three controllers. The step-down transformer feeds the primaries of the pre-boost transformers, and also feeds the autotransformers. Taps from these autotransformers, in turn, feed the series transformers, whose secondaries energize a 3-phase capacitor bank (upper right). The controllers, of which a detailed circuit diagram is shown at the bottom, drive a set of three single-phase servo-motors M through 12 V relays until there is null VAR output from all three transducers; i.e., until power factor compensation has been attained.

Operation of the controller:

The motor-load is connected in parallel with the delta-connected 240 μF capacitor bank. This capacitor bank receives its energy through the preboost and series transformers. The series transformer is connected to three single-phase variable transformers (variacs) which are governed by servo-motors M inside each controller-unit. Each servo-motor is energized through a pair of 12V relays.

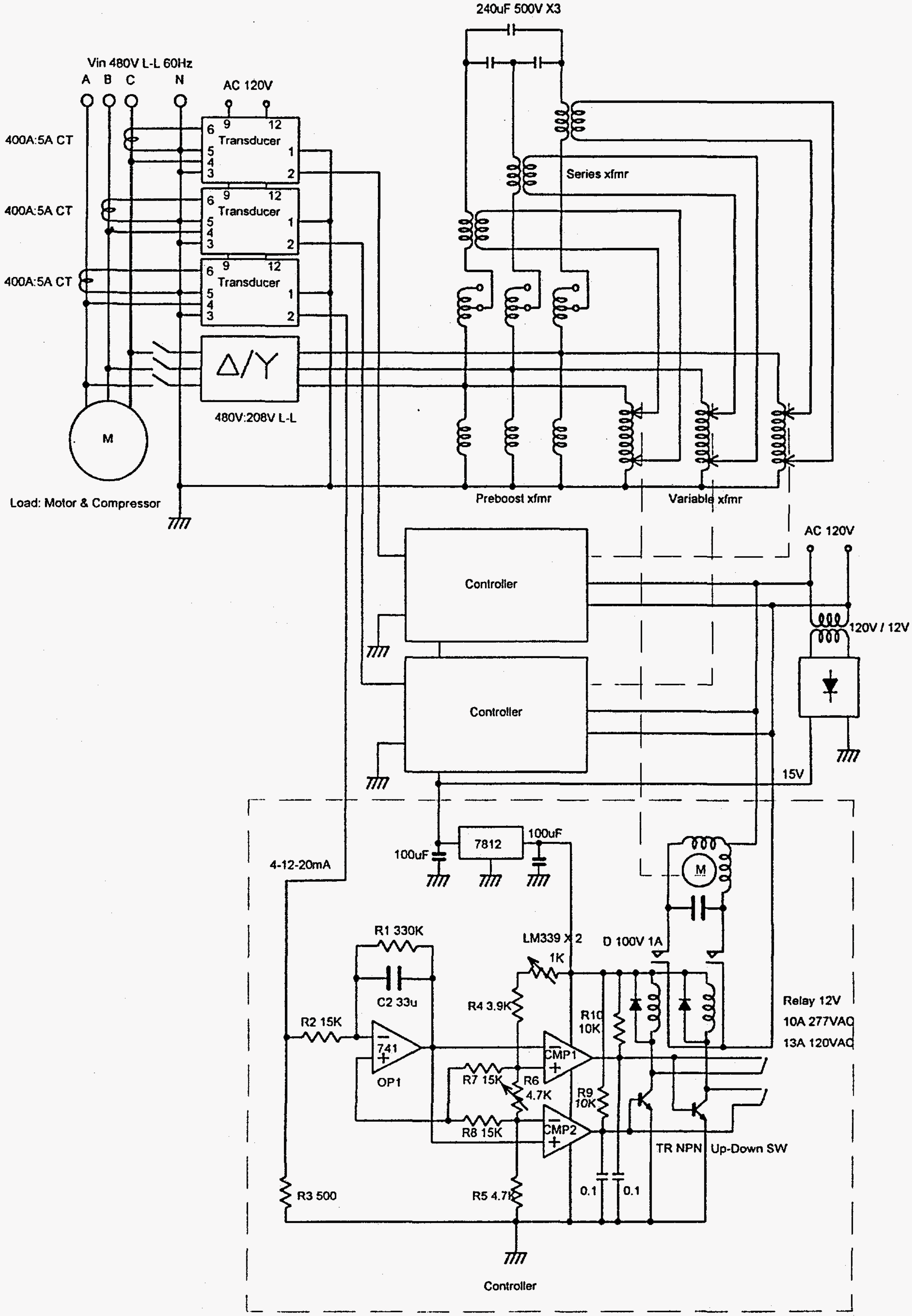


Fig. 4: Detailed diagram of the prototype and the testing arrangement

Six input current, input voltage control signals are supplied to the three VAR transducers (top left, Fig. 4). A VAR-control signal is generated by each transducer, and is transferred to its controller. This VAR-control signal is proportional to VAR's per phase required by the motor-load. The controller integrates that signal at OP1 to reduce noise and to provide a time delay for the response. The time constant of this delay is determined by R2 × C2, and has a value of $15k \times 33\mu F = 495$ msec; about half a second. The output of OP1 is then compared with a reference value by comparators CMP1 and CMP2 to switch the motor on and off. That reference value is generated by the resistor-group R4, R5 and R6. Resistor R6 provides a window of control voltage to prevent unnecessary switching of the 12V relays. R6 is needed for the following reason: Due to the relatively long mechanical time-constant of the variac, small changes in the control voltage may result in too many on/off switchings of the servo-motor M, and consequently too many small movements of the variacs: not an efficient way to change the power-factor. R7 and R8 are used to obtain a neutral point of the window which will be used as a reference point for the output of the VAR transducer.

At the neutral point, the VAR transducer generates 12 mA, and this current will generate 6V across R3 (12 mA $\times 500 = 6$V). (The neutral point can also be set to 6V by adjusting R4.) When the inductive component of the load increases, the output signal of the VAR transducer is reduced below 12 mA. This results in a decrease in the voltage drop across R3, and OP1 integrates that voltage change. The output of OP1 will be compared with the reference voltage of R7 and R8. When that output is decreased below the window voltage of R6; i.e., when the output of CMP2 becomes larger than that of CMP1, the left-side relay will switch on. Then, the servo-motor will change the brush-position of the left-side variac. The voltage at the extreme left corner of the capacitor-delta-bank will increase. Subsequently, that will increase the capacitive current that compensate for the additional inductive current of the motor-load. This control process will continue until the output of the VAR transducer reaches a value of 12 mA, which is the neutral point. It should be noted that for a symmetrical load, such as a motor-load, all three phases will act simultaneously.

Test results:

Results of tests without and with the power factor (PF) correction unit are shown in the tables below. Test 1 was intended primarily to measure how effectively the compensating unit was able to correct the PF's of high and low PF loads. Test 2 was intended to assess the repeatability of the results. Test 3 was intended to measure the inputs to the PF correction unit itself.

Data were obtained using the following instruments: Fluke Model 41 Power Harmonics Analyzer. This device allowed us to measure voltage, current, power, VAR's, power factor, and total harmonic distortion. In addition, it provided the V and I waveshapes, and analyzed the harmonic content of each. The time required for full power factor correction was about 6 secs after an abrupt load change.

<u>Test 1 - Power Factor Compensation Test</u>

	Without PF unit	With PF unit
High power load	V = 283 V I = 179 A P = 43 × 3 kW **PF = 0.88** VA = 50 × 3 kVA	V = 285 V I = 165 A P = 46 × 3 kW **PF = 0.99** VA = 47 × 3 kVA
Low power load	V = 285 V I = 59.9 A P = 10.6 × 3 kW **PF = 0.61** VA = 17.2 × 3 kVA	V = 287 V I = 44.6 A P = 12.6 × 3 kW **PF = 0.99** VA = 12.7 kVA

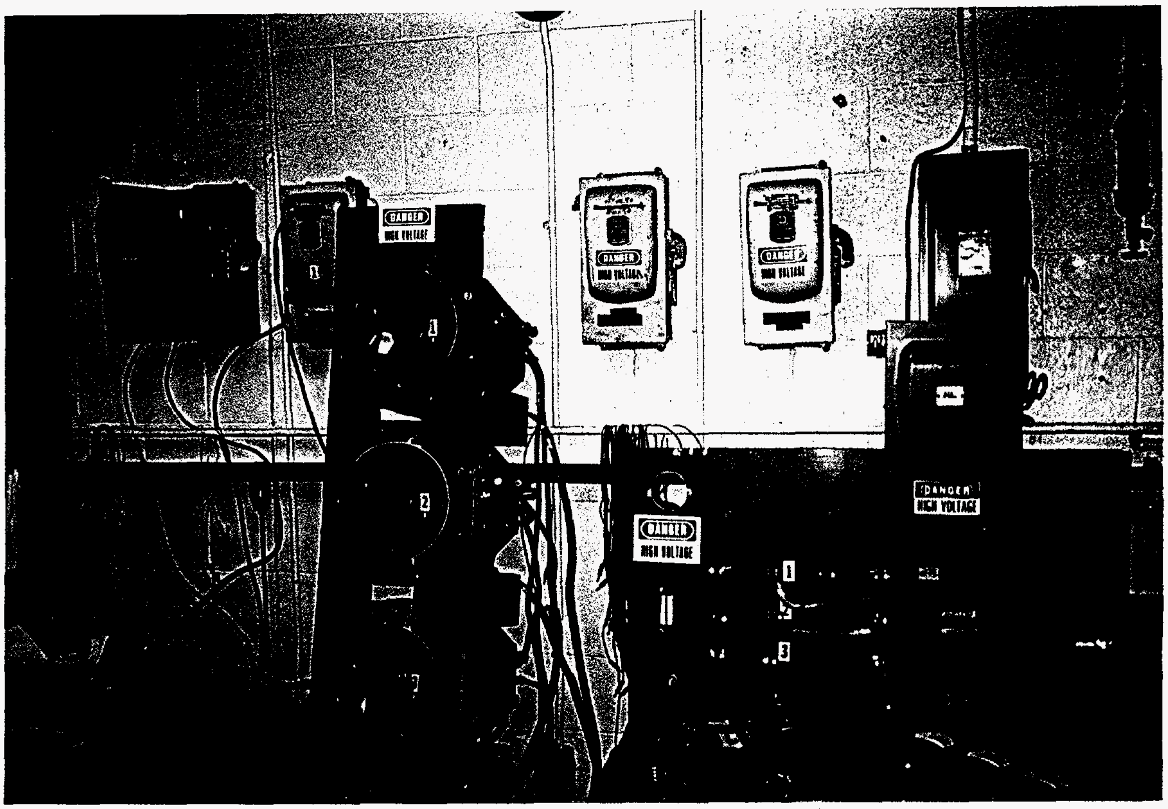
Test 2 - Repeatability Test

	Without PF unit	With PF unit
High power load	V = 281 V I = 180 A P = 43 × 3 kW **PF = 0.88** VA = 49 × 3 kVA	V = 283 V I = 165 A P = 46 × 3 kW **PF = 1.00** VA = 46 × 3 kVA
Low power load	V = 283 V I = 60 A P = 10.8 × 3 kW **PF = 0.64** VA = 17.1 × 3 kVA	V = 285 V I = 43.1 A P = 12.3 × 3 kW **PF = 0.99** VA = 12.4 × 3 kVA

Test 3 - Measurement of Input to PF Unit Itself

	Load with PF unit	Input to PF unit only (including the Δ/Y Xfmr)
High power	V = 282 V I = 167 A P = 45 × 3 kW PF = 1.0 VA = 45 × 3 kVA	V = 281 V I = 69.8 A P = 1.9 × 3 kW PF = 0.1 VA = 20 × 3 kVA
Low power	V = 284 V I = 43 A P = 12.3 × 3 kW PF = 0.99 VA = 12.4 kVA	V = 283 V I = 50.3 A P = 1.4 × 3 kW PF = 0.1 VA = 14.1 × 3 kVA

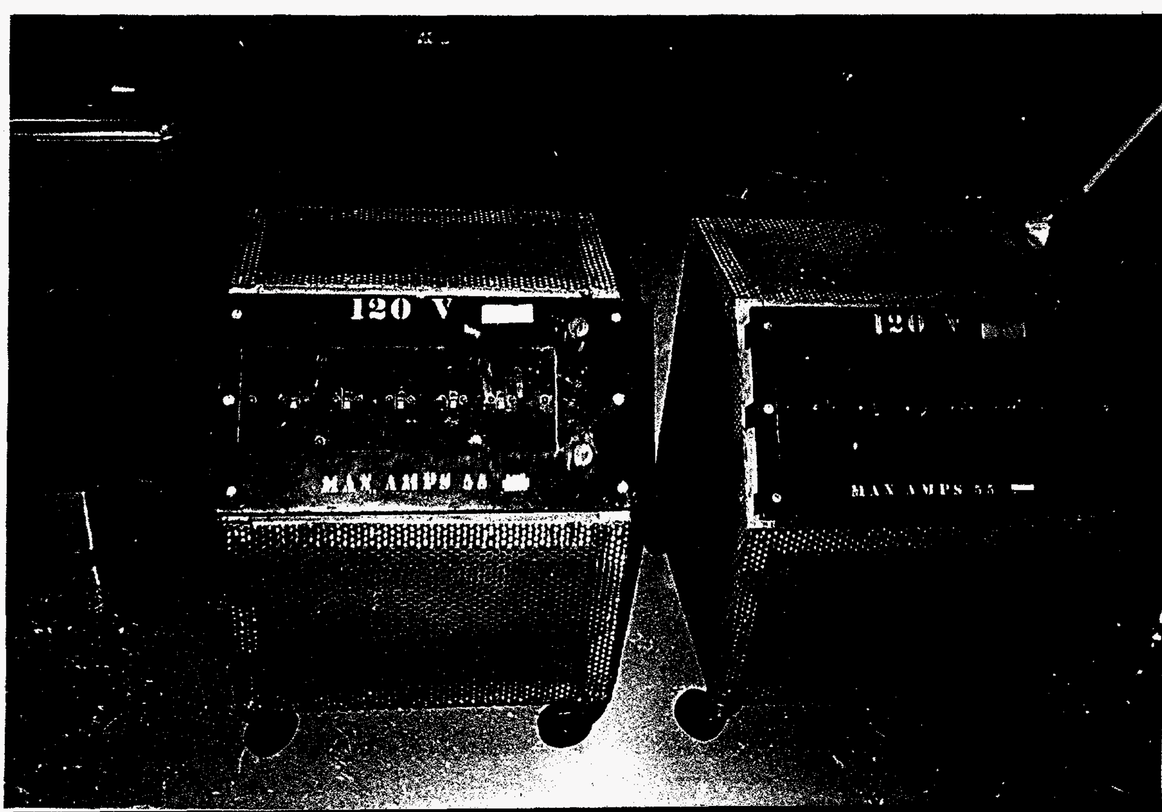
In summary, the device described here successfully corrected the power factor of a 150 hp motor / compressor to 0.99 whether operating at full load or idle; was mechanically and electrically robust; and took a relatively short time (less than 6 seconds) to accomplish full correction. The simplicity of the device suggests that it has an inherent reliability that may not be present in more complicated schemes.



LABORATORY TEST FACILITY

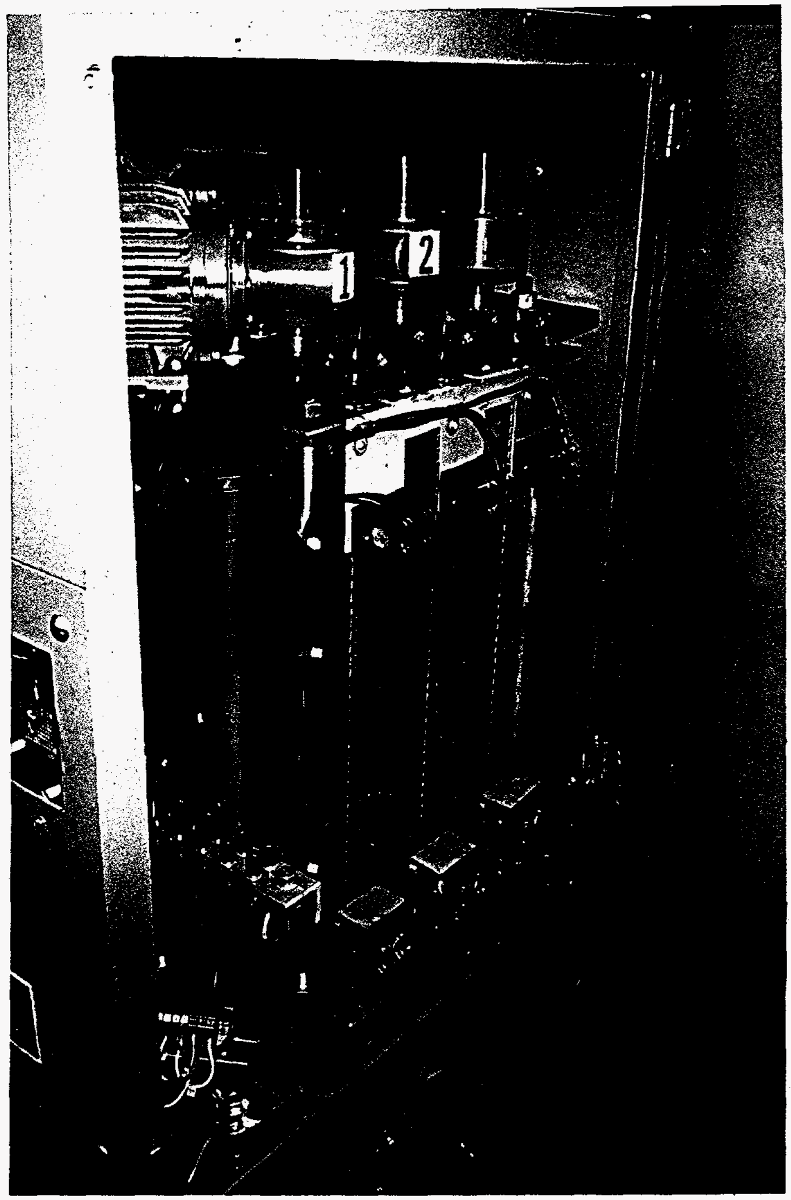
Above: The laboratory was set up to allow independent control of each phase thus providing the team with safety and flexibility in testing. Pictured are the vertically mounted Powerstat Variable Autotransformers for voltage control, test bench with several meters and wall mounted, fused, disconnect switches.

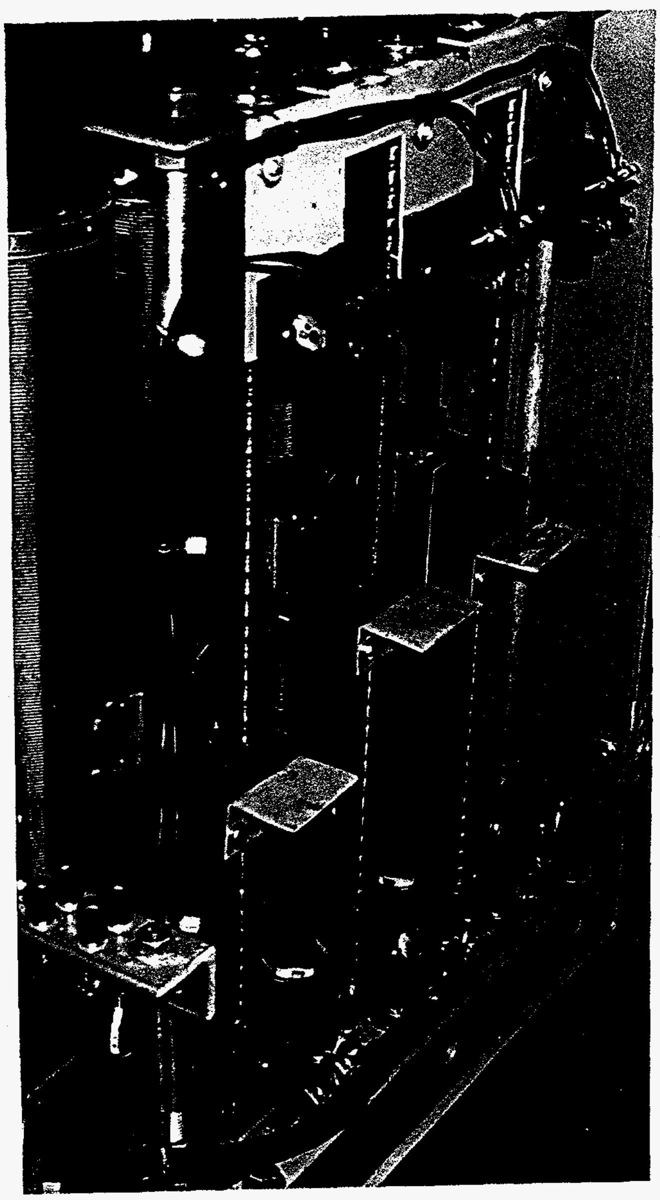
Below: Two of the selective resistance units used in the lab to apply loads to the power factor correction system by phase.



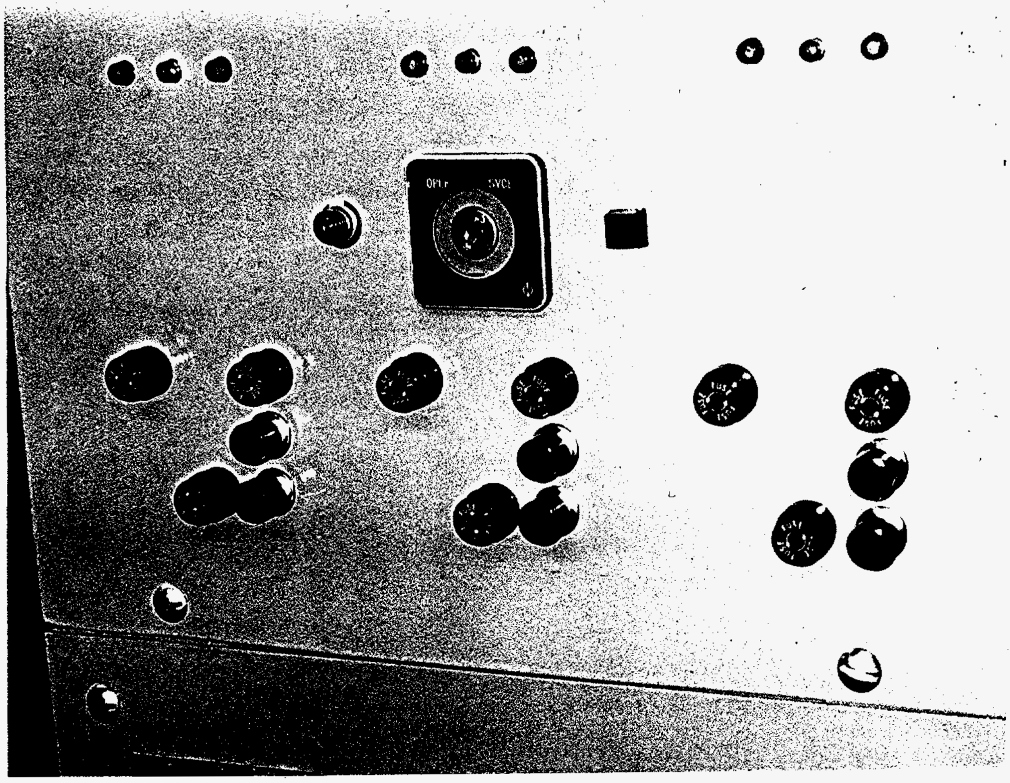
VARIABLE TRANSFORMER

Right: Three Motors individually modulate the taps for each phase by turning the screw gear. Photo shows the taps in the lower position.





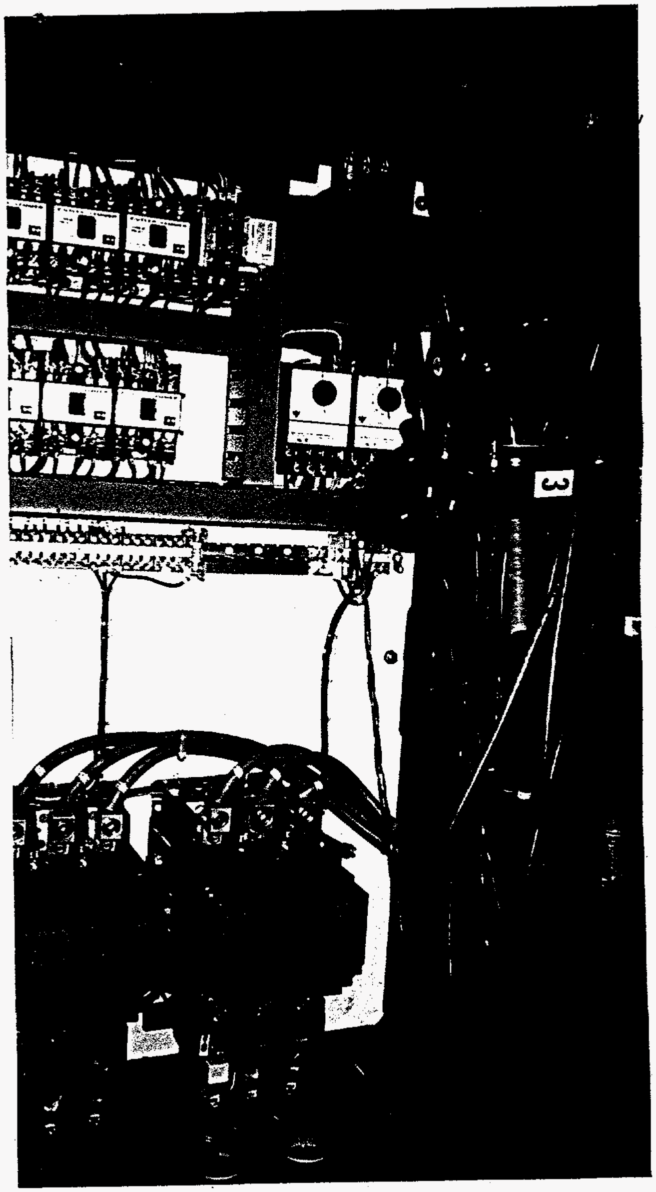
Left: Taps are moved by motors to optimum position to regulate the voltage and attain the best power factor correction. Notice the switches set above and below the taps to limit the travel at the end of each screw gear.



SAFETY SYSTEMS

Individual control and motor fuses (**see top photo**) were used to protect the system controls. LED pilot light confirm the integrity of the circuits. Manual override - up/down buttons allowed the variable transformer taps to be moved independent of the custom made power factor controllers.

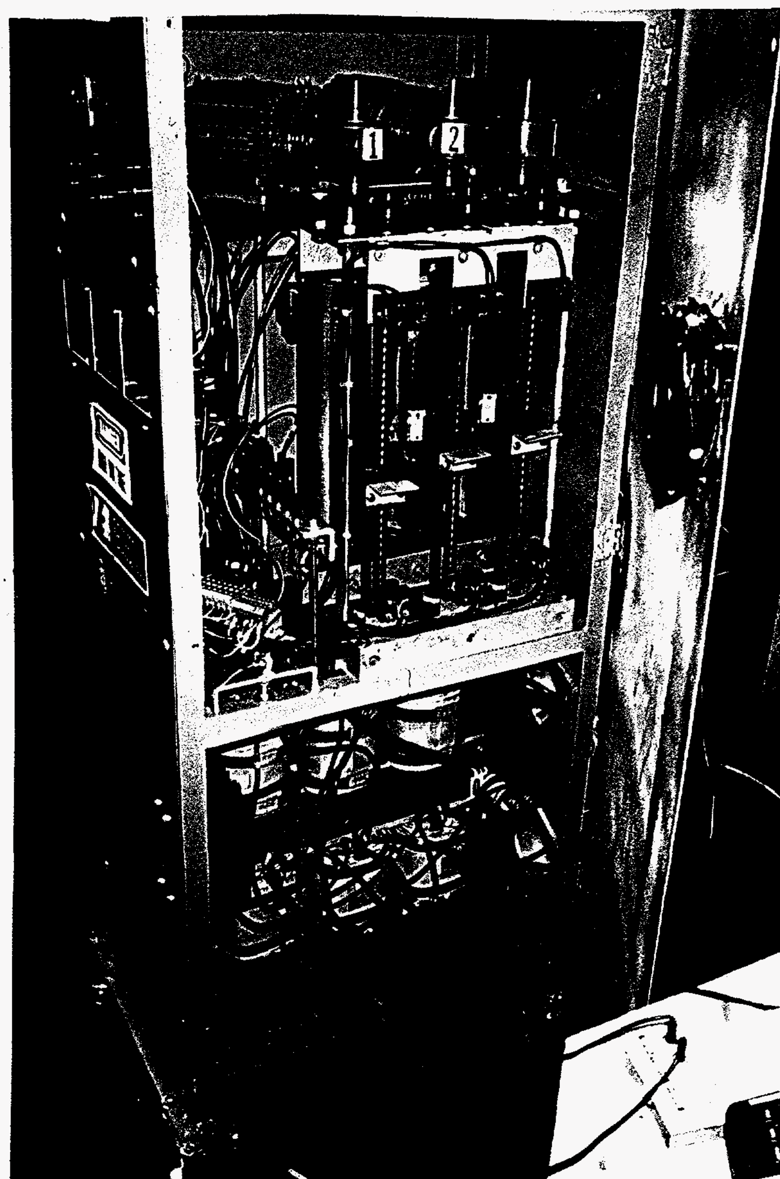
The **photo at right** shows a fused disconnect switch mounted on the rear of the power factor correction system. The switch contained a lock that prevented operation of the unit when specific personnel where not in attendance at the site.

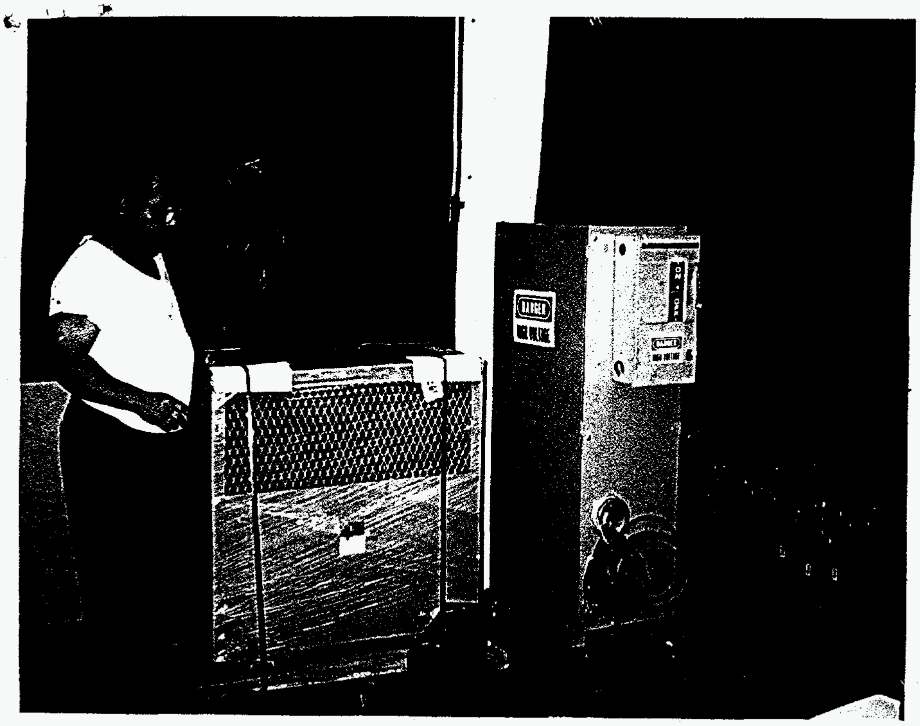


Left: Inside view of control panel of compressor reveals transducers on the power lines used to feed load data to the controllers on the PF Correction unit.

WIRING

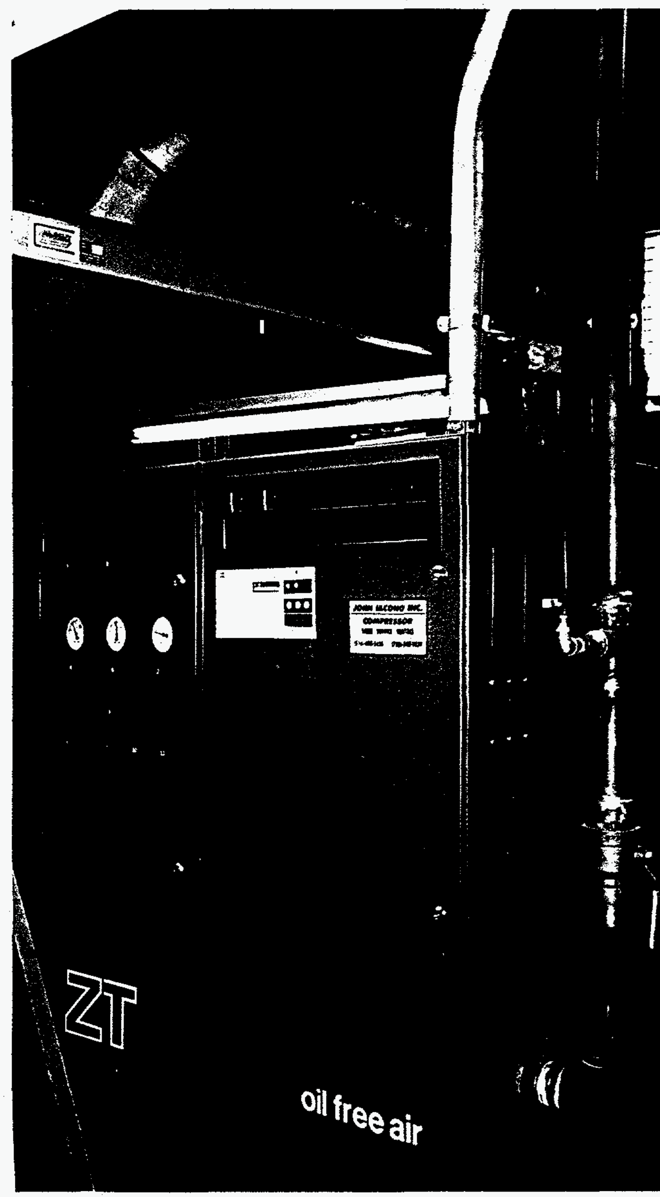
Right: Access door open, the PF correction system wiring can be seen. Note addition of circuit breaker on front panel and air ventilation exhaust fan on access door.

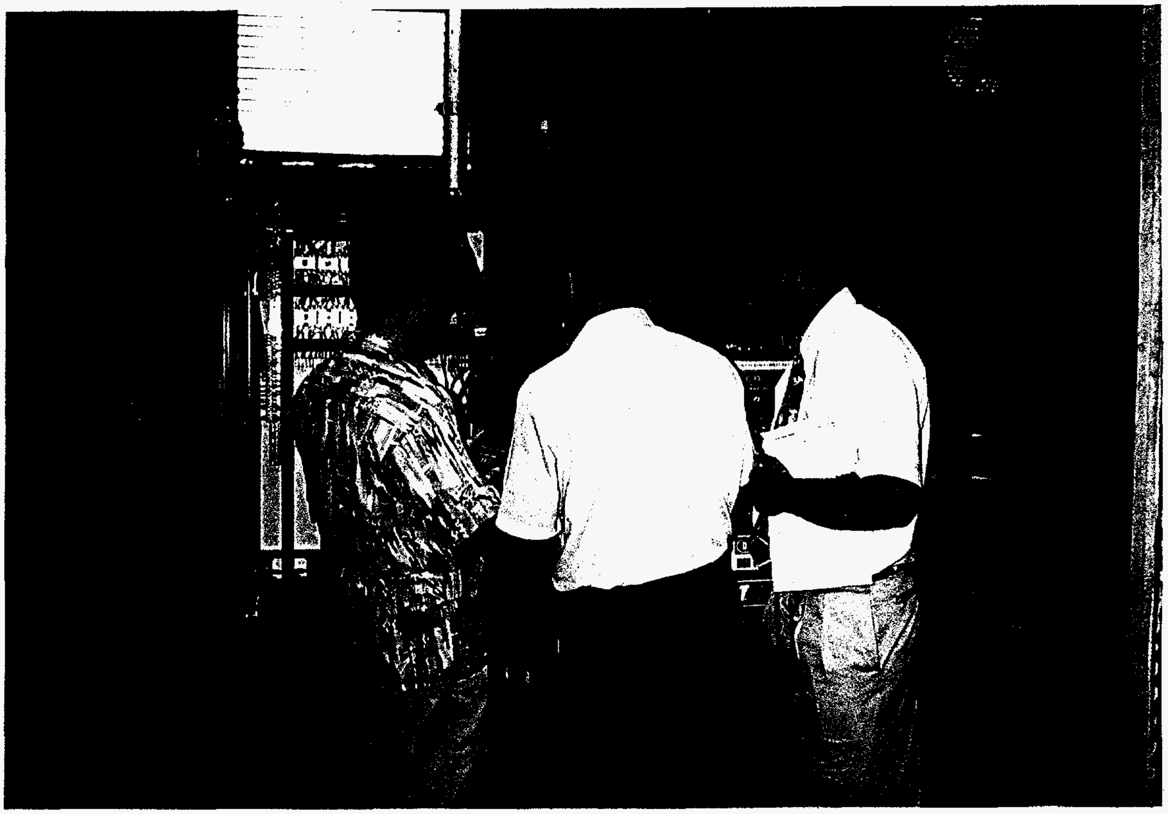




DELIVERY / INSTALLATION

Above: Equipment is trucked from lab to industrial site, lowered by fork lift into building and then and rolled into place.
Right: PF Correction system is located in proximity to access door on Compressor.
Below: IET equipment is unpacked and readied for test installation wiring.

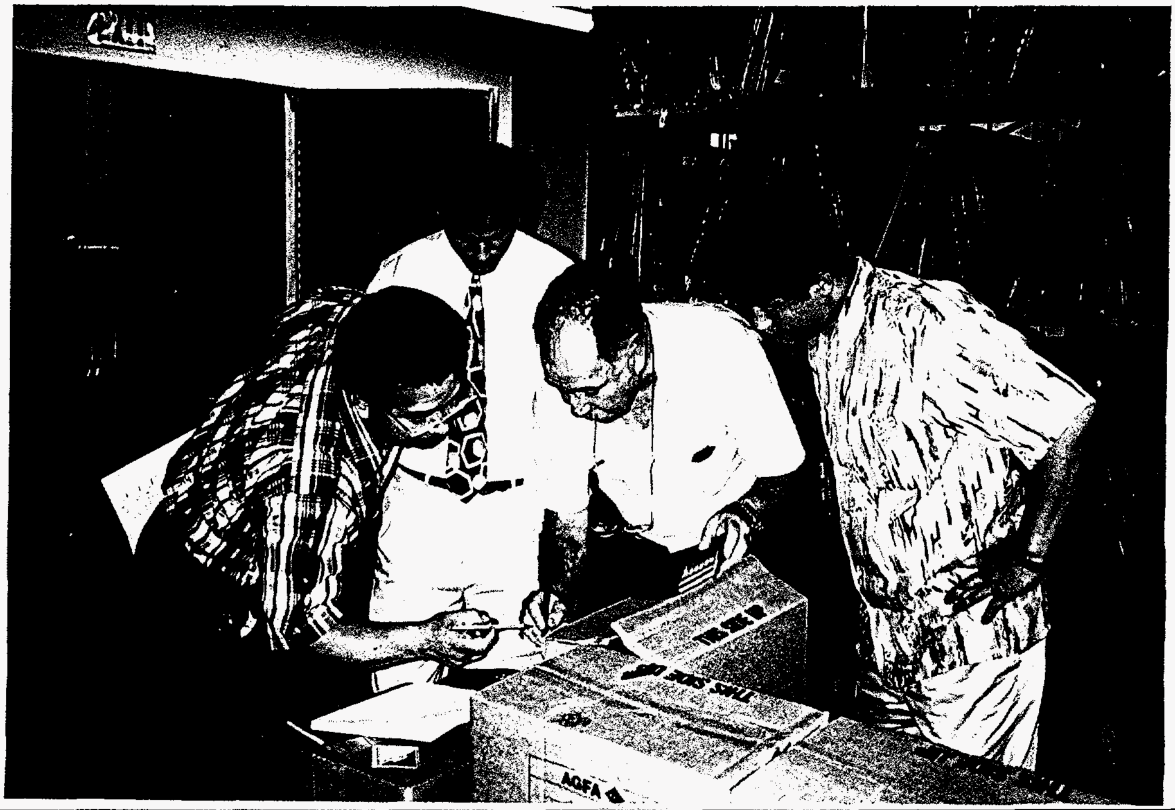


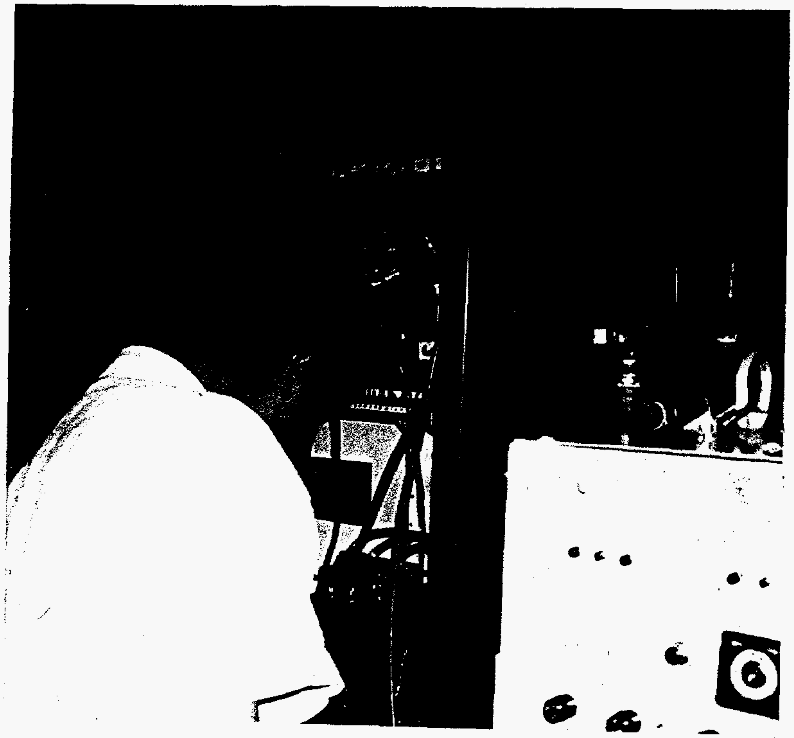


MONITORING / LOCAL UTILITY

Top: Monitoring readings from recording meters, team members Dong Ho Lee (Fellow, Polytechnic University) Dr. Zivan Zabar and Long Island Lighting Company engineer (local utility) Ayad Aqeel verify data output.

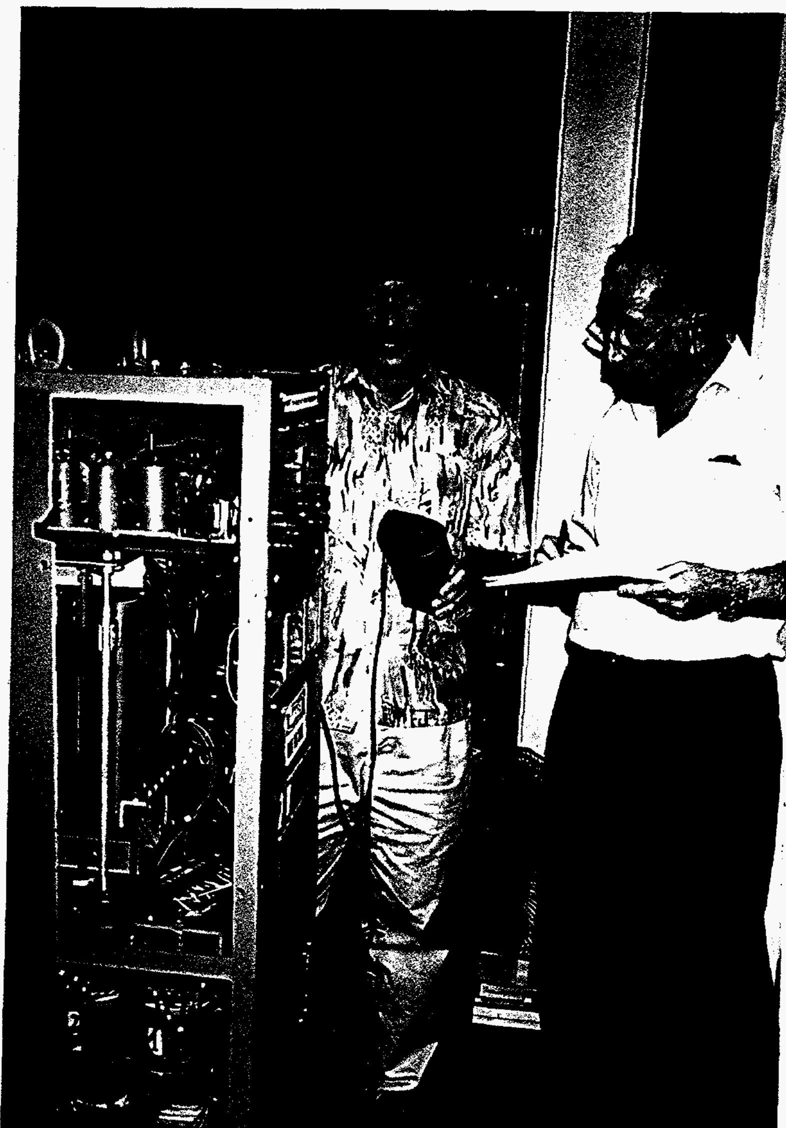
Below: Team reviews findings between readings. At left is Jaime Bayona, team technician.

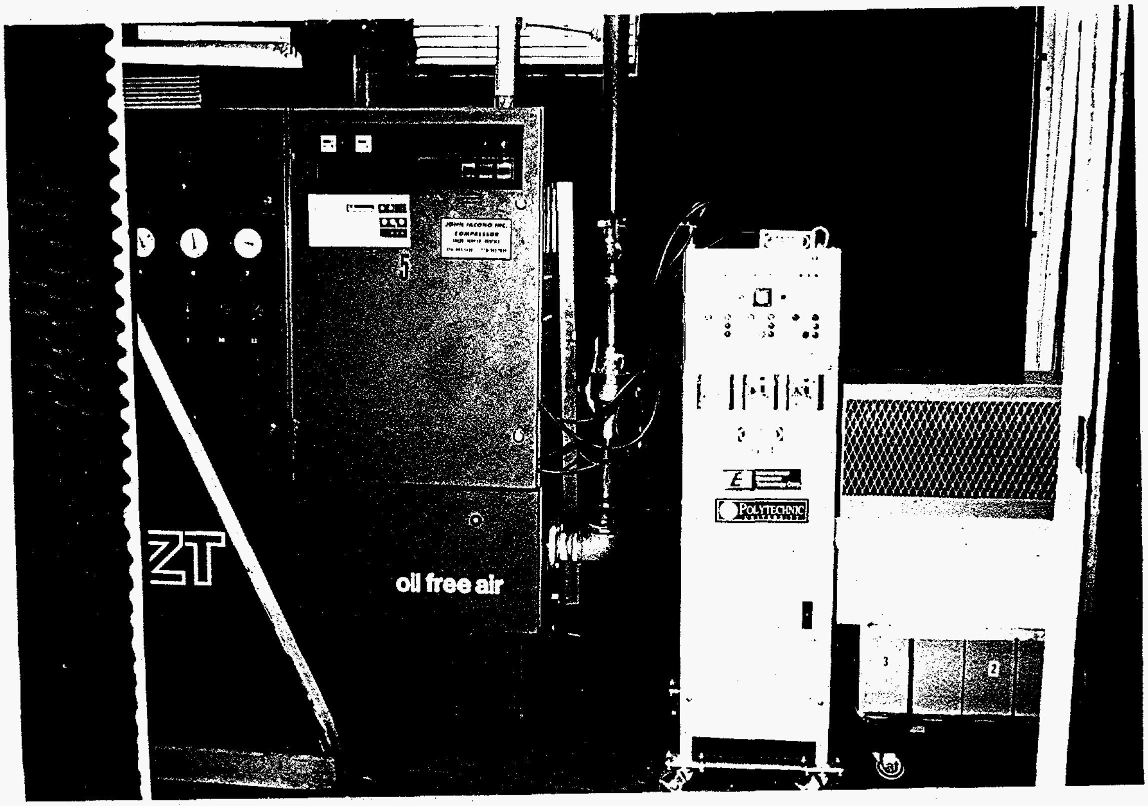




MONITORING

Team members monitor voltages, amperage and power factor correction readings on portable recording meter/analyzer. Numerous readings were obtained on each phase before and after the compressor, before and after the power factor correction unit and at each capacitor and transformer. Readings were then recorded for our final report. Testing continues.





SITE SELECTION / EQUIPMENT

Above: A heavy duty compressor application was selected where we could monitor rapid and often changes in load. The photo shows (left to right) the compressor system, the power factor correction system, transformer and capacitors.

Below: Open control panel of compressor shows preliminary wiring to our equipment.