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# Trimode Optimizes Hybrid Power Plants Final Report: Phase II



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Prepared by Sandia National Laboratories Albuquerque, New Mexico 87185
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# Trimode Optimizes Hybrid Power Plants

## Final Report - Phase II

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**ABSTRACT**

In the Phase II project, Abacus Controls Inc. did research and development of hybrid systems that combine the energy sources from photovoltaics, batteries, and diesel-generators and demonstrated that they are economically feasible for small power plants in many parts of the world. The Trimode Power Processor reduces the fuel consumption of the diesel-generator to its minimum by presenting itself as the perfect electrical load to the generator. A 30-kW three-phase unit was tested at Sandia National Laboratories to prove its worthiness in actual field conditions. The use of photovoltaics at remote locations where reliability of supply requires a diesel-generator will lower costs to operate by reducing the run time of the diesel generator. The numerous benefits include longer times between maintenance for the diesel engine and better power quality from the generator.

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## INTRODUCTION

Work on the Trimode Power Processor Small Business Innovative Research Grant was completed ahead of schedule and on target with the budget under the guidance of Alec Bulawka, US DOE Project Manager, with the National Photovolataic Program. All technical objectives for the Phase II program were achieved. In this final report each of the five project tasks is discussed.

After evaluating the Sandia test results, an improved design for equalize battery charge evolved for Task 3, Three Phase 50 kW Trimode, and this design is reported below.

The Trimode has been applied to a fuel cell project, thus demonstrating the versatility of its three modes of operation and ability to adapt to specific project needs. In the DC power supply mode, the DC is used to generate hydrogen fuel for energy storage.

By way of background, Abacus Controls Inc has supplied its Bimode Power Processors for two prototype projects in the United States. Both systems were modified in the field to transfer load from the bimode in the inverter mode of operation to the diesel generator in six steps because the diesel generators could not take a full load transfer without severe transients in both voltage and frequency. Thus the Trimode Power Processor developed under the U S Department of Energy Grant DE-FG05-94ER81689 proved to be the best solution in both of these applications.

The U S Park Service awarded Abacus a contract for a 30-kW Trimode to be used in the Channel Islands. Abacus management recognized that if this unit were used for the Sandia tests in Task 4, then the budget to build a three-phase Trimode for testing could be reallocated to other tasks. Permission was granted by both the U S Department of Energy and the U S Park Service to do this.

## TRIMODE POWER PROCESSOR

The Trimode power processor is designed to use the same power switching components and filter in each of several modes of operation. The three primary modes of operation from which the name is derived are stand-alone mode; utility-tie mode; and battery-charge mode. As described in this report, the Trimode power processor is designed to work in hybrid power systems. Its use with a diesel-engine and a photovoltaic array (combined with a maximum power tracker) is the primary application envisioned for remote installations. In this section, more technical details of the Trimode are described, with emphasis on the unique parallel mode of operation. In this parallel mode of operation, the Trimode can change instantaneously from delivering energy to the battery to removing energy from the battery; this change can occur multiple times within one cycle of the voltage waveforms.

This mode of operation has been defined to be "utility-interactive."

In the stand-alone mode, the Trimode acts as an inverter. The diesel-generator is not present, and the Trimode controls the voltage at the load to be a sinusoid at the correct rms value. The technique used for the control is the Sinedynamic® controller strategy developed by Abacus Controls and used throughout the product line. This is a deadbeat control strategy. Each period of the voltage waveform is divided into sampling instants, nominally 96 for most products at Abacus, but as high as 252 as discussed below. At each sampling instant, the present output voltage and its derivative are sampled. These sampled values are used to predict the output voltage at the next sample instant, and compared to the desired voltage at the next sample instant. From this difference, the switch duration required to obtain that output voltage is computed. The output LC filter plays a crucial role in these computations (as discussed in the literature for the deadbeat control strategy[1]) since the variable being controlled is the output voltage.

In the other modes of operation, the Trimode controls the current at the output of the diesel-generator to be sinusoidal and phaselocked with the voltage from the diesel-generator. Thus, in the other modes, the Trimode is a current-controlled device.

In the battery-charge mode, the current drawn from the generator is controlled to be a sinusoid in phase with the voltage. This minimizes the harmonic content of the current drawn by the Trimode. In the parallel mode of operation, the Trimode may be designed to provide a sinusoidal current to the load, again in phase with the voltage.

This discussion for either the battery-charge mode or the parallel mode of operation leads naturally to considering what is really desired in a hybrid energy system. What is desired is to extract as much energy as possible from the renewable energy source and to consume as little fuel as possible in the diesel-engine-generator. Diesel engines are most fuel-efficient, measured in watts generated per fuel flow, when operated at full load, with a current waveform that is sinusoidal and in phase with the diesel engine voltage. Thus, the optimal strategy for the Trimode, when operating in any mode other than the inverter mode, is not to control its own current, but to control the current out of the generator. The current out of or into the Trimode will be whatever is necessary to force the current out of the diesel-generator to be a sinusoid at the full load level. According to this strategy, the Trimode implicitly decides at each sample instant whether to consume or deliver power; for the three-phase version, this decision is made for each phase. The Trimode changes from consuming to generating power many times per cycle if necessary. Also, in this process, all of the harmonic current is supplied by the Trimode.

In the test results shown below, the Trimode accomplishes the goal of switching between generating and consuming power multiple times per cycle. The Trimode operates in parallel with the diesel to effectively increase the peak power of the system to be the sum of the power rating of the diesel-generator and that of the Trimode. The Trimode can be switched between the inverter mode and the parallel mode of operation seamlessly; this is important in order to eliminate the transients in the voltage waveform out of the diesel-generator that are often observed when switching on a load.

Note that the Trimode can be modified to generate other waveshapes if that is desired in a particular application. For example, in some telephone applications, a trapezoidal waveshape for the current is desired. This can be accomplished using the same strategy described below.

## TASK 1 POWER QUALITY ENHANCEMENT CONTROLLER

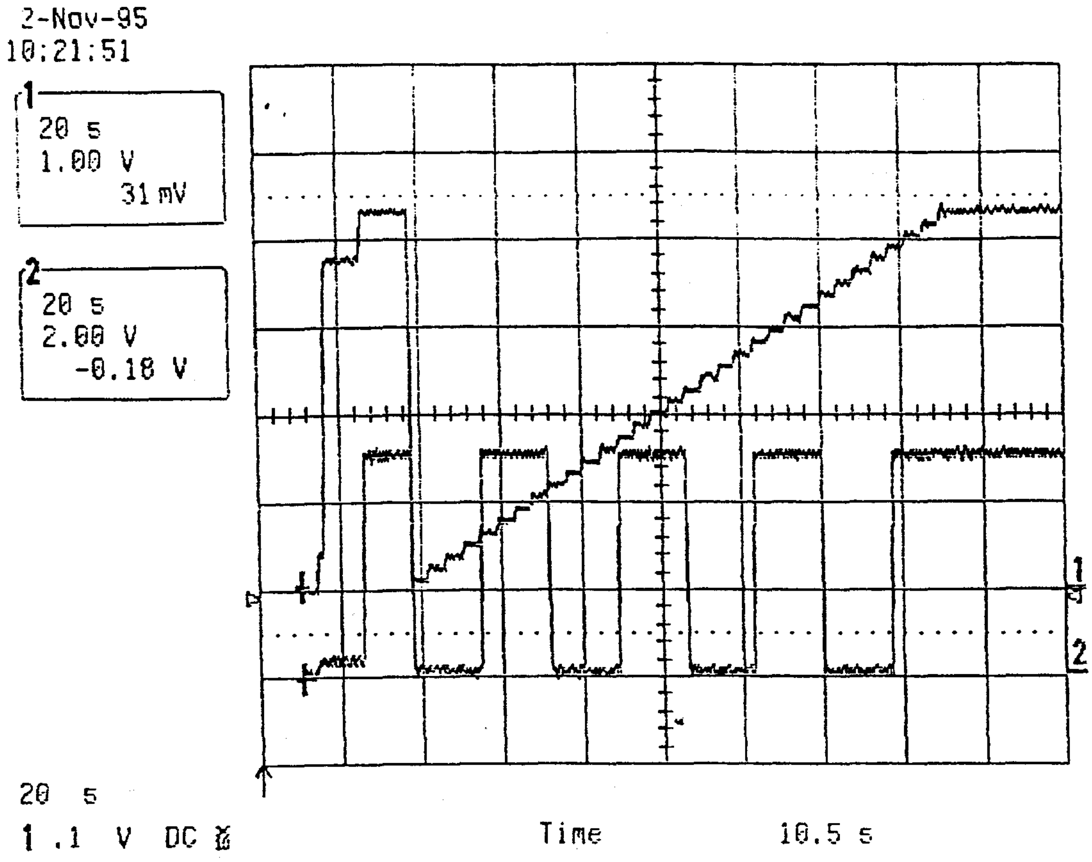
The primary design of the Power Quality Enhancement (PQE) Controller was completed in September 1995. Subsequent improvements included the capability to operate at a sampling rate of either 192 or 252 samples per cycle. For 60 Hz operation, this implies a sampling rate of up to 15120 Hz. The Altera EM5128 ASIC, with 128 programmable macrocells, was selected as the primary controller element for the single phase model.

Research and development continued with a complete breadboard of the PQE Controller. Testing and debugging in October and November 1995 resulted in a working model that meets all of the system goals.

One of the important features of the Trimode Power Processor is its smooth transfer of power, both from the inverter to the diesel-generator and from the diesel-generator to the inverter. During both transitions the power supplied by the diesel-generator is controlled by the PQE Controller while the Trimode either supplies any additional load current demanded by the load or converts any additional available generator current into battery charging.

Figure 1 illustrates a turn-on followed by a transfer to diesel-generator. The upper trace is the PQE reference; the lower trace counts every four steps (not significant). Each horizontal scale box is 20 seconds. The transfer from inverter mode of operation to parallel mode of operation occurs at the sharp drop in the reference. Load is applied to the diesel-generator in 32 equal steps of approximately four seconds each. With load step changes of 3%, the gradual loading of the generator will be indiscernible.

When the system battery is fully charged, the load is transferred to the inverter and the diesel-generator is turned off. Figure 2 shows the removal of load from the diesel-generator in 3% increments. The transfer to inverter mode of operation from parallel mode of operation occurs at the sharp rise in the reference trace in Figure 2.




# FIGURE 1
TURN ON AND INVERTER TO DIESEL TRANSFER

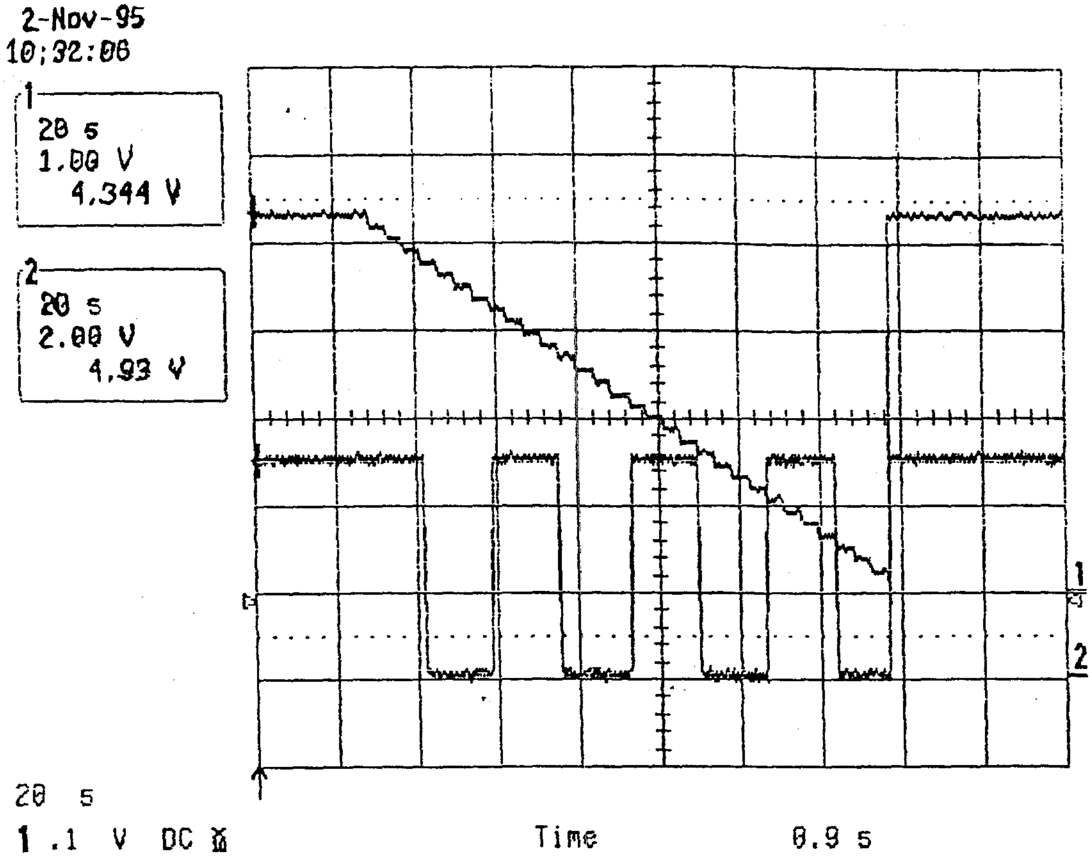



FIGURE 2
DIESEL TO
INVERTER TRANSFER

## IMPROVED POWER QUALITY ENHANCEMENT CONTROLLER

Experimental results are reported for an improved PQE Controller in the section for Task 5, Three-Phase 300-kW Trimode for village sized systems. The dual-bridge concept has been demonstrated for a single-phase model. The PQE Controller has been extended to 252 steps per cycle to minimize the size and cost of filter components in large system applications or in lower power applications where size is critical.

For a derivation of the dual-bridge sampled-data-control equations, refer to APPENDIX A.

## TASK 2 SINGLE-PHASE 5-kW TRIMODE

The 5-kW Trimode Power Processor was thoroughly tested, with the utility substituting for a diesel-generator and using the PQE Controller from Task 1.

Figure 3 shows the current reference signal (outer trace) and the actual current returned to the utility line (inner trace) for the 192-step sample-data PQE Controller. Note that current returned to the utility is the "new" or third mode for the Trimode Power Processor.

In the inverter mode of operation, turn-on into an unknown load requires a rapid but controlled increase in voltage to the load to avoid transformer flux saturation and to charge computer grade capacitors over several cycles. A digital technique has been incorporated into the PQE Controller design, and the results are illustrated in Figure 4. The voltage reference, shown as a staircase in Figure 4, increases 3% in 32 steps every half cycle. The linear ramp output of the inverter is also shown in the figure.

## TASK 3 THREE-PHASE 50-kW TRIMODE

As stated in the Introduction, the need for a three-phase Trimode Power Processor is well established. The level of sophistication in the diesel-generator start/stop control algorithm extends from the simplest single battery low-voltage start point/high-voltage stop point to a computer controller that precisely keeps record of the state-of-charge. The controller at the Naval Air Weapons Center Superior Valley installation, our 300-kW Bimode Power Processor with twelve 25-kW PV arrays and maximum power trackers, uses an IBM Valuepoint Computer and National Instruments LabView software and combines battery management with other controller tasks, the power safety system, a data acquisition system and status displays for the diesel-generator, battery, PV arrays with their maximum power trackers, and our Bimode Power Processors. Navy personnel can make modifications as operating experience evolves.

The Superior Valley-type controller would not be cost effective at 50 kW PV hybrid

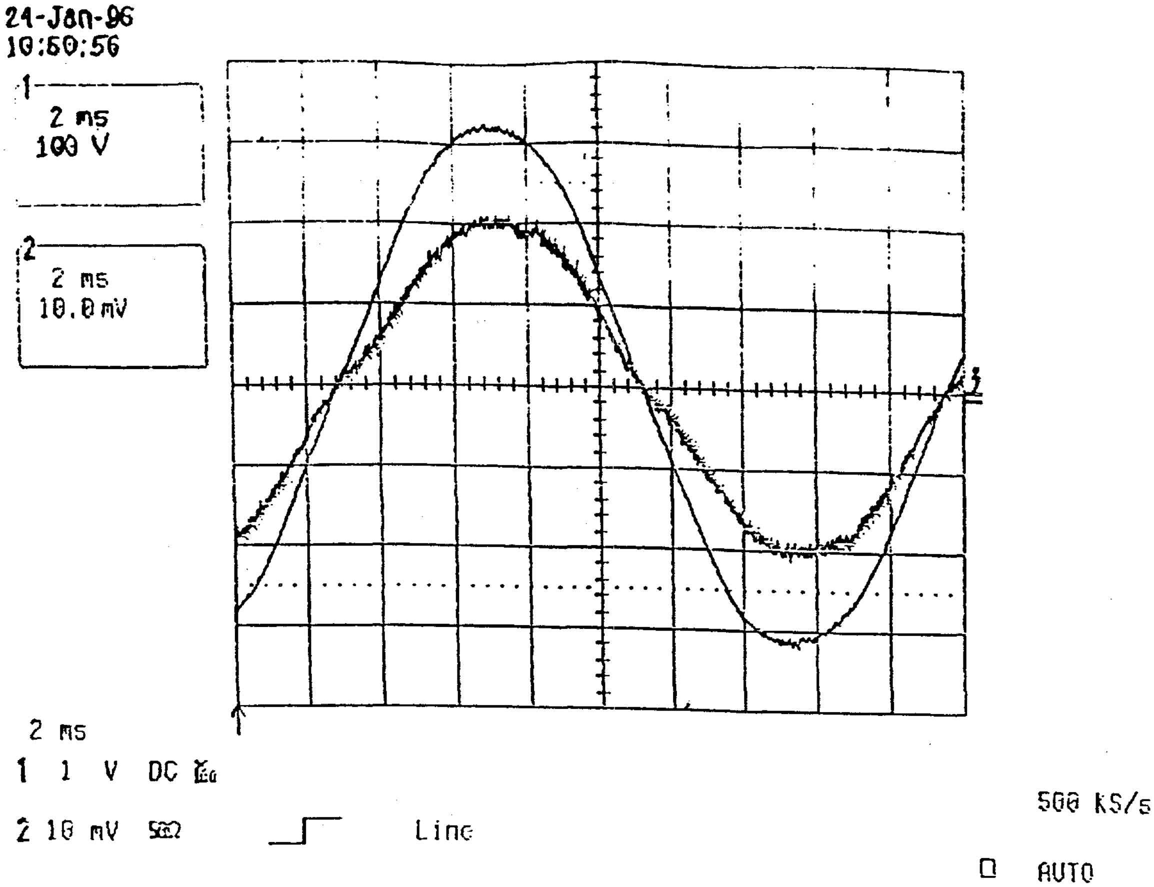
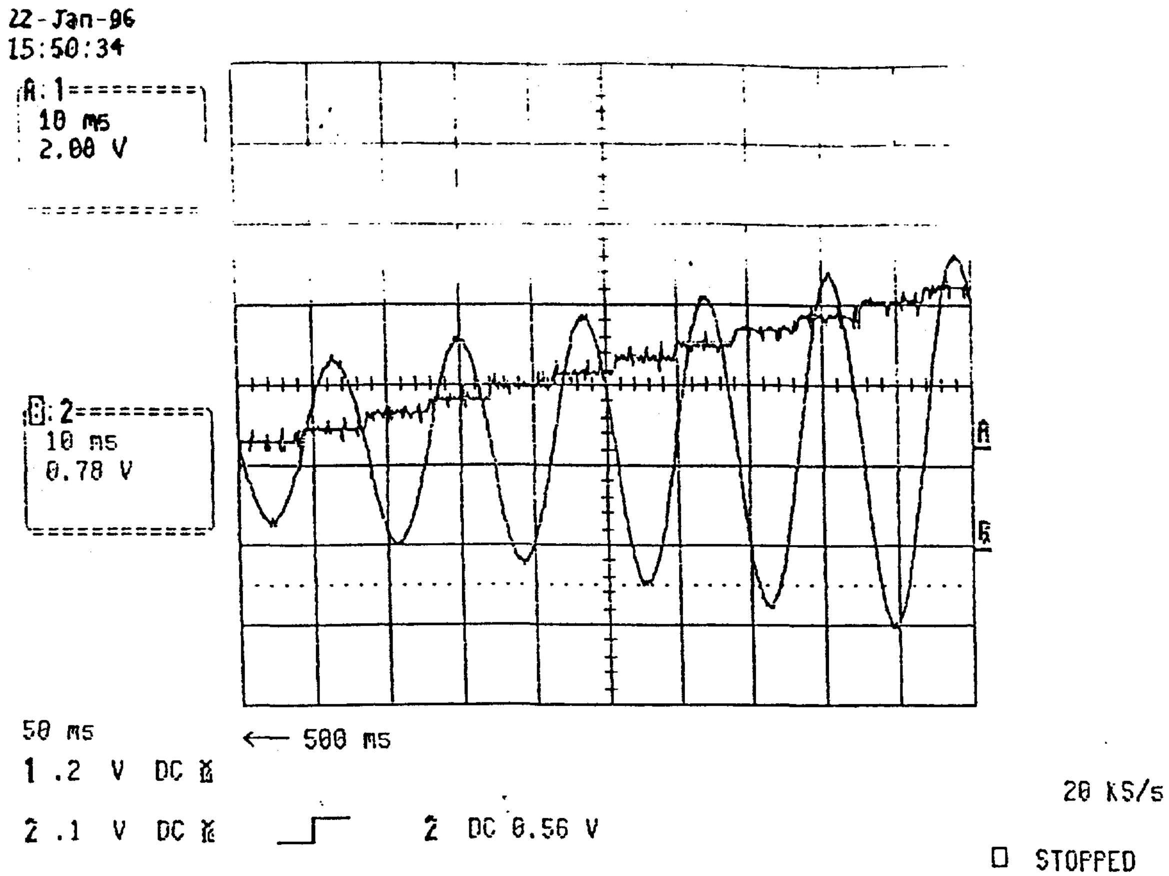



FIGURE 3
5KW TRIMODE CURRENT
ADDED TO THE UTILITY




# FIGURE 4
# DIGITAL SOFTSTART FOR THE 5KW TRIMODE

installations. The question is what can be added at minimal cost within the structure of the planned hardware. The answer is that two added enhancements can reduce diesel-generator running time. Both originate in the maximum power tracker, which monitors both the PV array and the battery.

The first is to add an option to compensate for battery temperature; this is germane to shelters that are unprotected from ambient temperature changes. The Carol Spring Mountain PV hybrid power generator has temperature compensation, so this feature has been added without cost to the SBIR project.

The second is to add compensation for time of day. The battery is allowed to discharge a little further at pre-dawn hours when the benefit of PV energy is anticipated. To implement this feature without the cost of an accurate clock, the algorithm uses an inexpensive crystal for tracking the time of day and makes periodic corrections with the oldest and most reliable time piece: the sun.

**Three-Phase PQE Controller**

The three-phase Bimode Power Processor has an individual controller card for each phase. Each card contains an ASIC and can serve either as the controlling phase, arbitrarily identified as phase A, or as the slave phase. The primary consideration in having individual control cards was to keep the control cards close to the power modules to minimize noise interference.

With the successful research, development and implementation of fiber optics under Sandia contracts AN9587 and AK5445 under the guidance of Dr. Russell Bonn, proximity between the control card and the power modules is no longer a necessity. Therefore, the research and development of a single-card, three-phase PQE controller was undertaken.

The Altera 100-pin EM5130 ASIC was selected as the main controller element, and extensive software development followed. The software was tested and debugged using the Altera Simulation Program. The total controller parts count has been reduced by greater than 50%, which improves reliability while reducing cost. A four layer printed circuit card was designed by Robert DeMilia of Abacus. The prototype card has been tested, qualified and shipped in the 30-kW Trimode at Channel Island.

The design of the three-phase Trimode for Channel Island required the addition of an "EQUALIZE CHARGE" to the battery charging function and a correction to the "time-of-day" set point for battery charging early in the morning; the generator will not be turned on if sunrise will occur within the next three hours. This is accomplished by temporarily lowering the LOW BATTERY set point. If early morning insolation is insufficient due to clouds or snow, battery charging from the TRIMODE will commence one hour after expected sunrise.

The first objective of the Trimode is to use all of the solar energy available. The second objective is to use the least possible diesel fuel consistent with long battery life. Normal system operation is shown in Figure 5, Trimode in inverter mode. The PV array delivers power to the maximum power tracker (MPT). The diesel-generator and the solid state relay are off.

The MPT seeks and holds the PV array at the voltage and current point on the IV curve that produces the maximum power possible at the given sun and temperature conditions. The output of the MPT is held at the voltage determined by the battery state-of-charge. The MPT makes a constant power transfer; so, the output current times the output voltage equals the input voltage times the input current times the efficiency. The efficiency is 97%.

With reference to Figure 5, current flowing from the MPT that is needed by the Trimode inverter avoids the inefficiency of battery charging/battery discharging by flowing directly to the inverter. The Trimode inverter operates at a constant AC output voltage and supplies power as demanded by the load.

At night, the PV array and the MPT turn off, and the battery supplies the retained PV energy to the Trimode inverter, which converts the power to AC for the load.

Figure 6 shows the Trimode in the battery charging mode. The diesel-generator is running and the solid state relay is ON to permit the diesel-generator power to flow to the load and through the Trimode to the battery. If the PV array has sufficient power to add to the battery charge, then solar energy also flows to the battery through the MPT. Field experience shows that the majority of the time the diesel-generator is turned on, the PV array and MPT are not on. With the "time of day" improvement in the MPT programming described below, it is unlikely that the diesel-generator will be turned on while the sun is shining.

The algorithm for this mode of operation is that the Trimode runs the diesel-generator at its rated load. The connected load takes what it needs, and the difference between the rated load and the actual load is applied to charge the battery through the Trimode.

### Equalize Battery Charge

All battery installations do not require a capacity to equalize charge, and some battery manufacturers who do require equalize charge recommend that equalization be accomplished at constant voltage, while others require that the total ampere hours discharged plus a fixed ampere hour recovery be applied to the battery. The Trimode design loads the diesel-

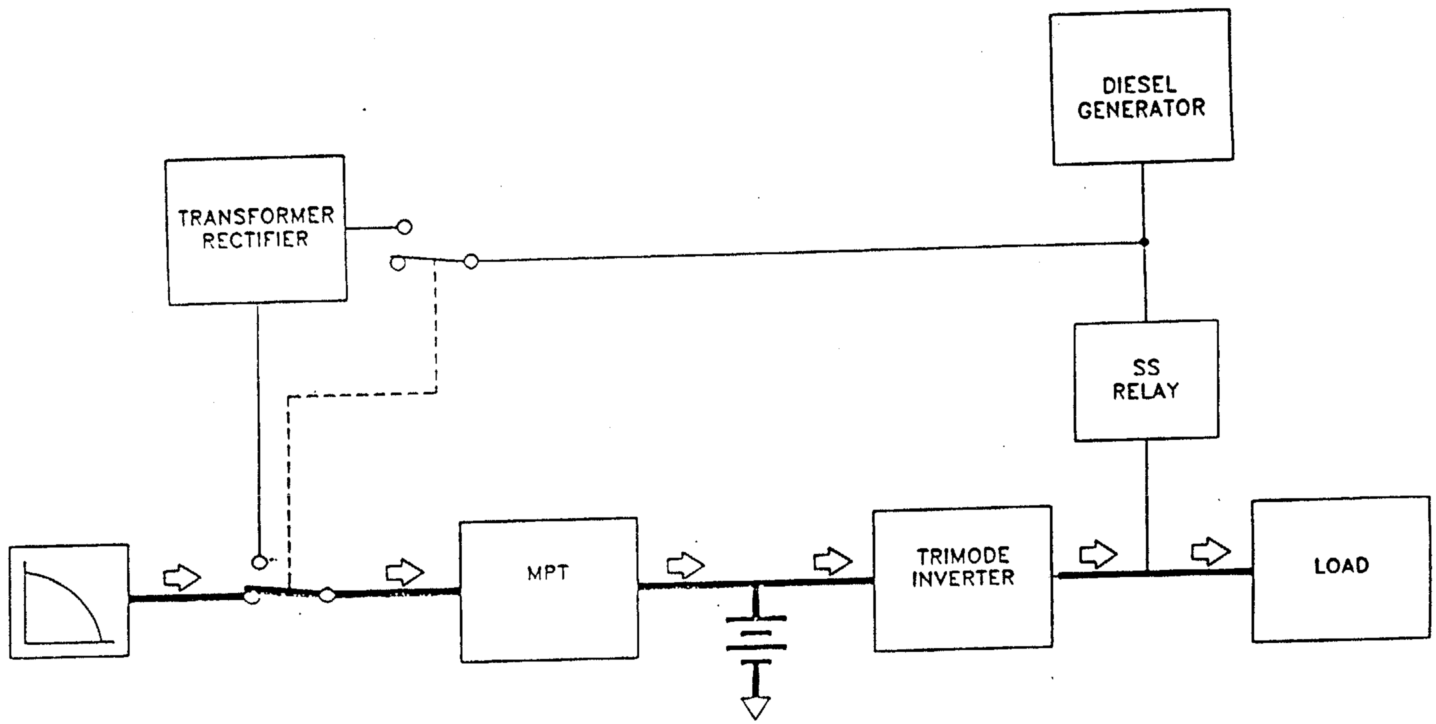



FIGURE 5
TRIMODE IN INVERTER MODE

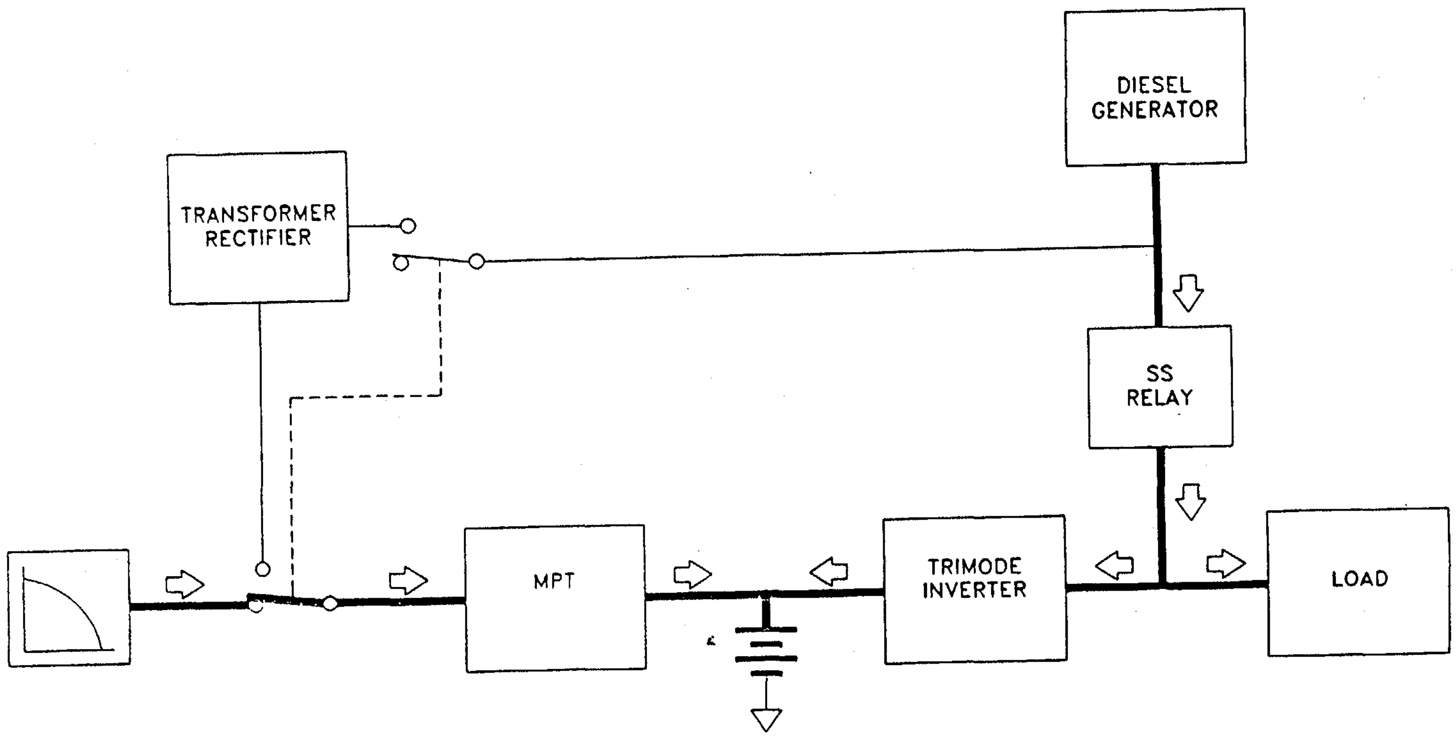



FIGURE 6
TRIMODE IN BATTERY CHARGER MODE

generator with a sinewave current on each phase, and this does not lend itself to a constant voltage equalize charge. So, for those battery installations that require a constant voltage equalization charge, a special configuration is required. The Channel Island 30 kW Trimode requires constant voltage equalization charge with adjustable voltage and adjustable time-of-charge.

Figure 7 shows the system configured in the equalize mode. The initial design of the Trimode took advantage of the constant voltage charging capability of the MPT. The diesel-generator is connected through an inexpensive transformer and six- phase rectifier to the input of the MPT. The MPT is set for a constant output voltage, the equalize voltage, and the battery is charged for the selected period of time.

During this mode of operation, the Trimode is off. The diesel-generator supplies the load through the solid state relay while supplying the power required for equalization.

The Equalize Flow Diagram, which depicts the applicable portion of the microprocessor instructions, is shown in Figure 8. F1 is the flag for equalize, and it is normally 0. Therefore the flow proceeds to the right of the F1 = 1 query. A request to equalize is a push button switch that reads "EZ = 0". When this occurs, flags and control bits are set for the PRECHG, which charges the battery with the Trimode until the equalization voltage VB_EZ is reached (the flow is down the second from the right column).

Ending this phase of the operation is signaled with CB4 = 0, at which time the program flow is down the second column from the left where the configuration transfer from Figure 6 to Figure 7 is accomplished and the equalization timer HRCTR is set in register R5. The transfer from Figure 6 to Figure 7 is rendered completely bumpless by walking down the Trimode command current until the trimode current is zero, at which point the Trimode is turned off.

Resister R5 holds the system in the Figure 7 configuration until time complete is signified by R5 = 0, at which time all of the flags and control bits are reset for the configuration in Figure 5 and the equalization charge is complete. The Trimode is turned on at zero current and a bumpless walk-in is accomplished.

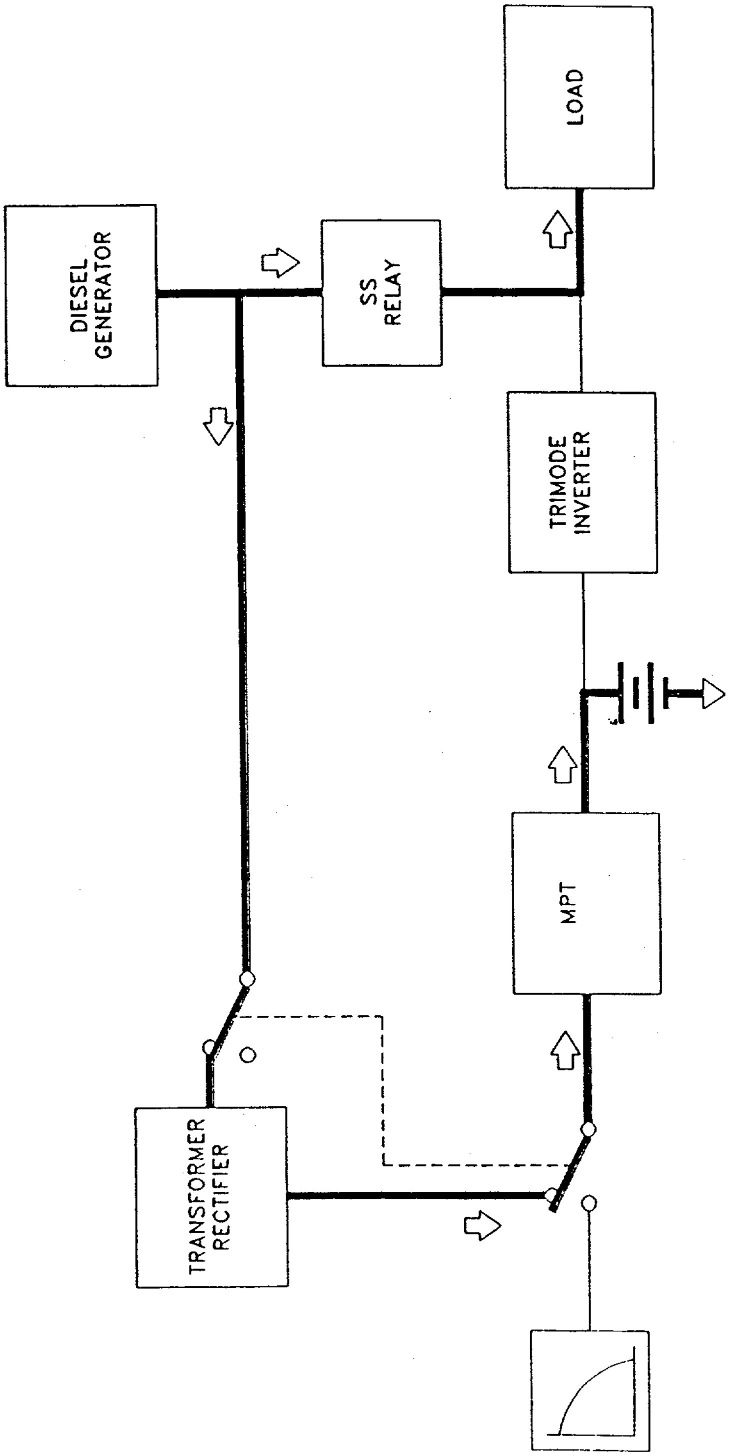



FIGURE 7
EQUALIZE MODE

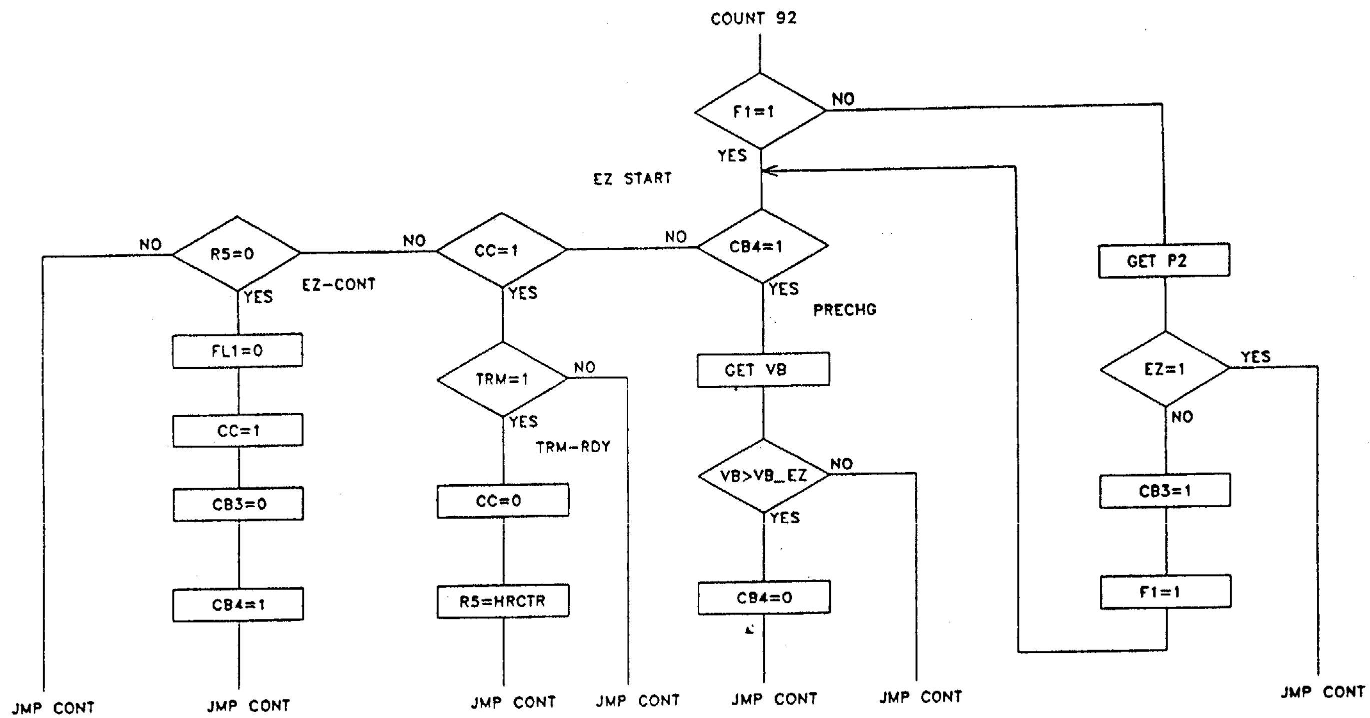



FIGURE 8 EQUALIZE FLOW DIAGRAM

## Time of Day

The flow diagram for the L COUNT/TIME OF DAY is shown in Figure 9. L COUNT is the code word for once through a complete microprocessor cycle, approximately 33 milliseconds. The L COUNT, the number of L cycles, is stored on register R4, which counts to 256. Register R3 is set to count 15 minute intervals. Register R5, as stated above, counts the equalization timer HRCTR when in the equalization mode. Register R2 counts the time of day, starting the day at sunrise.

With this background, the flow diagram may be read from left to right:

In the first column, if R4 has not decremented 256 times, jump out.

In the second column, reset R4 and decrement R3; if 15 minutes has not elapsed, jump out.

In the third column, 15 minutes has elapsed, R3 is reset and the next direction is set be whether in EQUALIZE or not; if in EQUALIZE, R5 is decremented, jump out.

In the fourth column, given a 15-minute interval and no equalize, if the time of day since the last sunrise has not reached 20 hours, jump out.

In the fifth column, it is past twenty hours; if the sun is not up and it is the first time through (TD FLAG = 0), the battery voltage low transfer is reduced. the reduced set point continues until the SUN UP? is YES.

With the SUN UP? = YES, the TD FLAG is reset and the VB low transfer is returned to normal.

## Model 639-4-240 Mechanical Design

The Model 639-4-240 is housed in a NEMA 12 cabinet and mounted on removable casters. The outline drawing, Figure 10, shows the dimensions, the location of interface parts, and the direction of air flow.

To assist the operator a mimic bus relating circuit breakers and meters to power flow is included on the front of Model 639-4-240. See Figure 11.

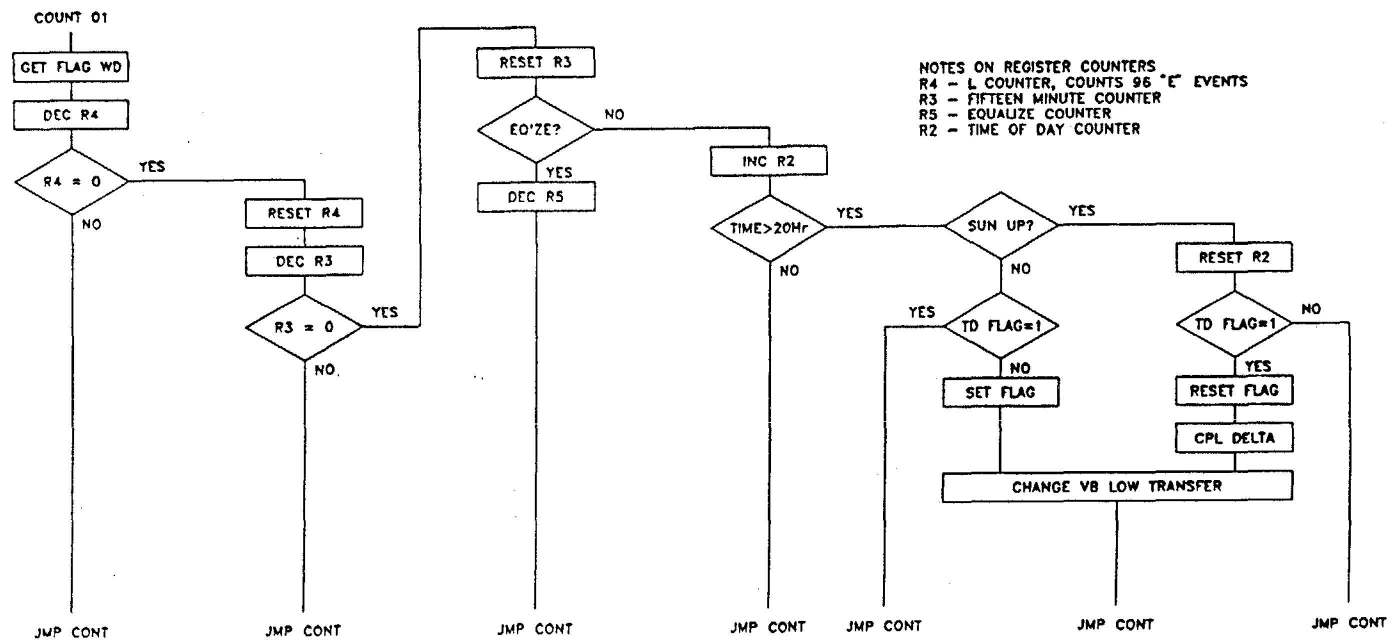



FIGURE 9 L COUNT/TIME OF DAY FLOW DIAGRAM

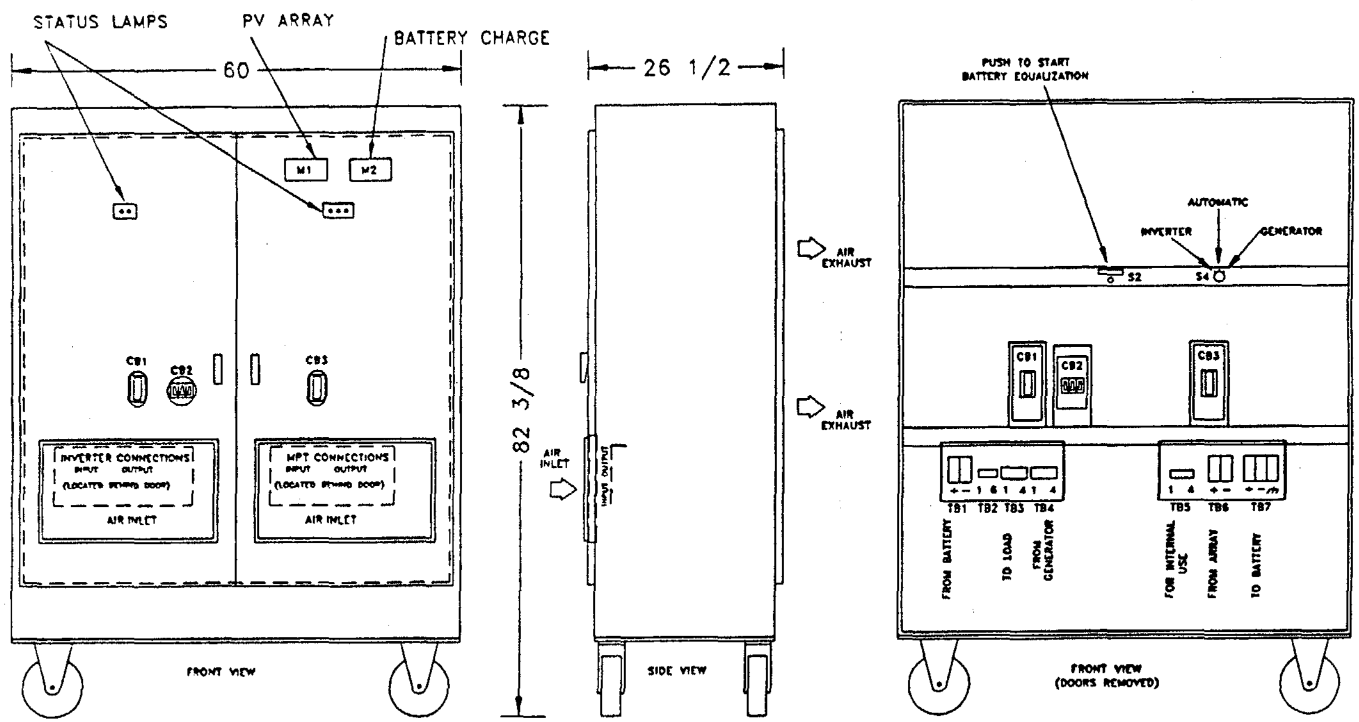



FIGURE 10 OUTLINE DRAWING MODEL 639-4M2

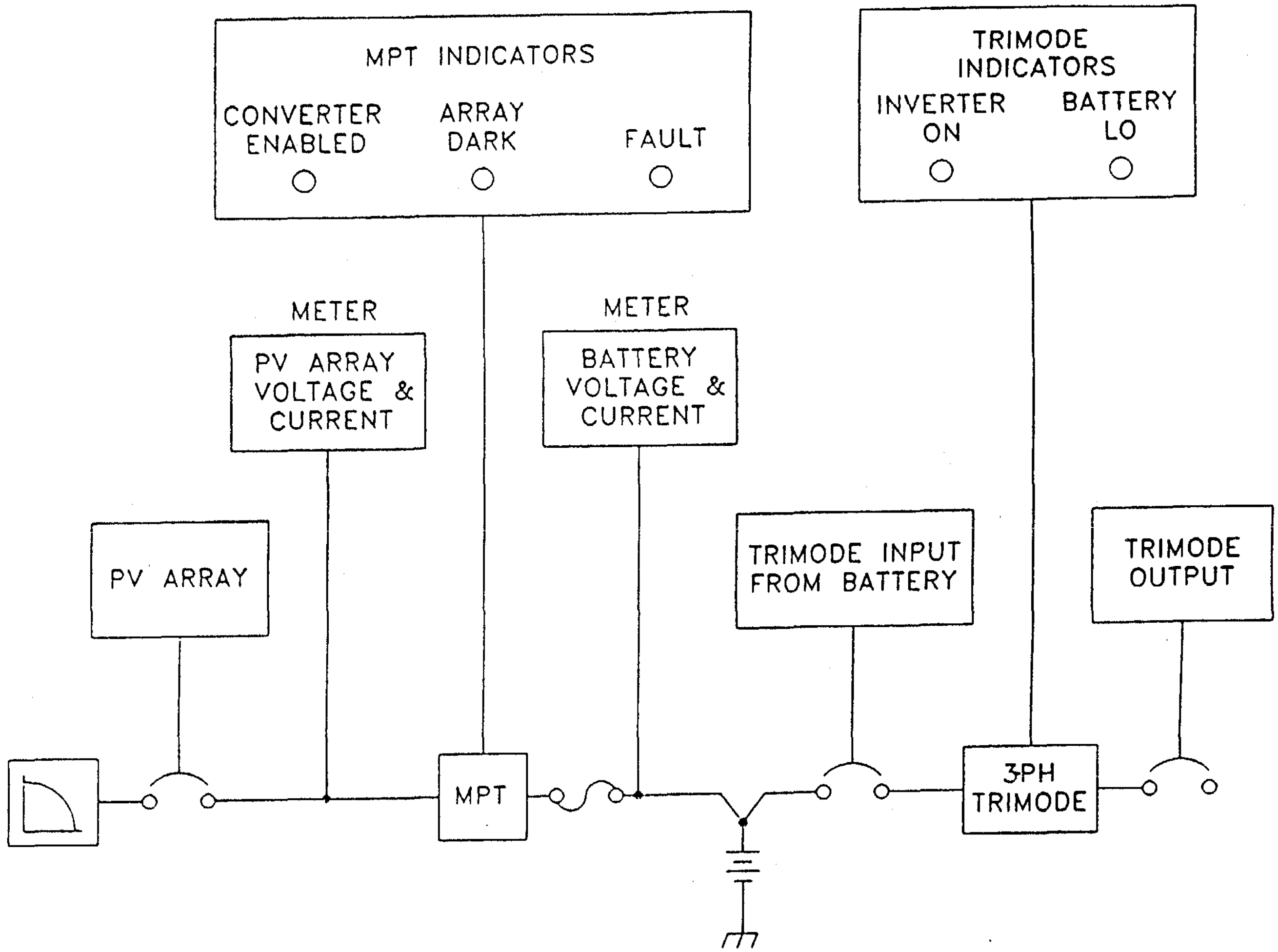



FIGURE 11 MIMIC BUS DISPLAY

## IMPROVED EQUALIZE CHARGE DESIGN

The constant voltage "equalize charge" as it was developed under this Grant and as it presently exists in U S Park Service Trimode Model 639-4-240 at Channel Islands is described above. Since that time a dual-loop design that combines the current-mode controller within the Trimode PQE with a constant voltage feedback loop at the battery has been invented, and this revised design is disclosed herein.

Figure 5, Trimode in inverter mode, Figure 6, Trimode in battery charge mode, and Figure 7, Equalize mode, appear earlier in this Report. Each figure shows the direction of power flow with an open arrow. In Figures 5 and 6 the transformer/rectifier is idle and the high power contactor at the Transformer/Rectifier input and the PV array output are in the NORMAL position.

In Figure 7 the transformer/rectifier is connected to the MPT to charge the battery at a constant voltage. In this configuration the PV Array is idle, the Trimode inverter is idle, and the current drawn from the diesel-generator is not sinusoidal, the last being an important feature of the Trimode in all other modes of operation.

In the improved design the transformer/rectifier and the high power contactor are eliminated, the PV array contributes all of the power that can be accepted, and the Trimode inverter performs the battery equalize function with the addition of less than $2.00 in parts cost. To better understand how the dual-loop works in the "equalize" mode, see the simplified Trimode control diagram in Figure 12. Figure 12A shows the diesel-generator rating setting the amplitude of the current sinewave generator as the reference to the Trimode control. Feedback of the diesel-generator current is used to keep the diesel power constant.

In Figure 12B, the current required to maintain the battery voltage at the equalize voltage automatically becomes the amplitude of the current sinewave generator. The diesel-generator no longer operates at full power because the battery charge rate is determined by the equalize characteristic of the battery rather than using the battery to absorb all diesel-generator power not delivered to the load.

In the equalize mode of operation the Trimode draws a sinusoidal current from the diesel-generator, and array power is applied to the battery as first choice over diesel-generator power. In other words, if the PV array can add energy to the battery during equalize, the diesel-generator automatically backs off its contribution.

The MPT will not allow the battery voltage to exceed its equalize voltage rating. This is accomplished by having the MPT operate at a fixed output voltage as an override condition to maximum power tracking.

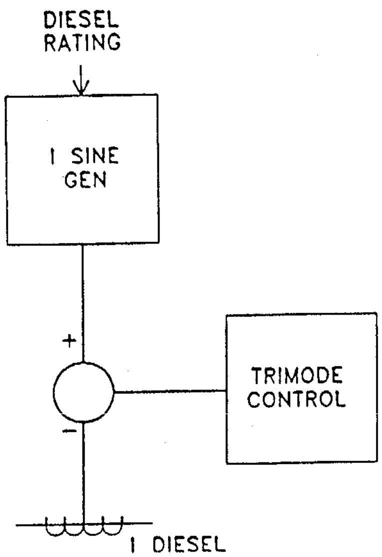



FIGURE 12A SIMPLIFIED TRIMODE CONTROL/ BATTERY CHARGE

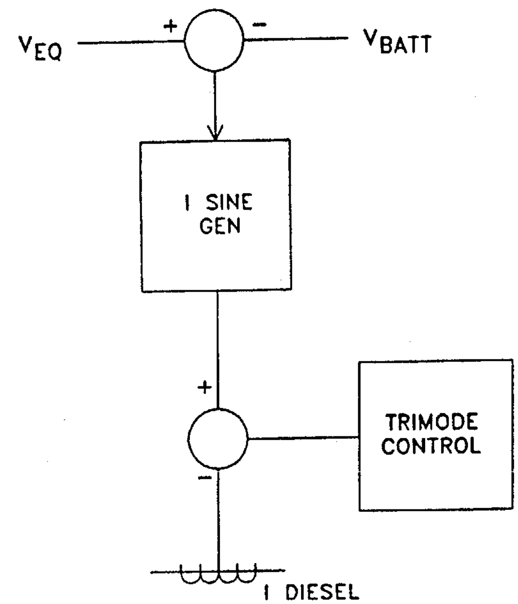



FIGURE 12B SIMPLIFIED TRIMODE CONTROL/ BATTERY EQUALIZE

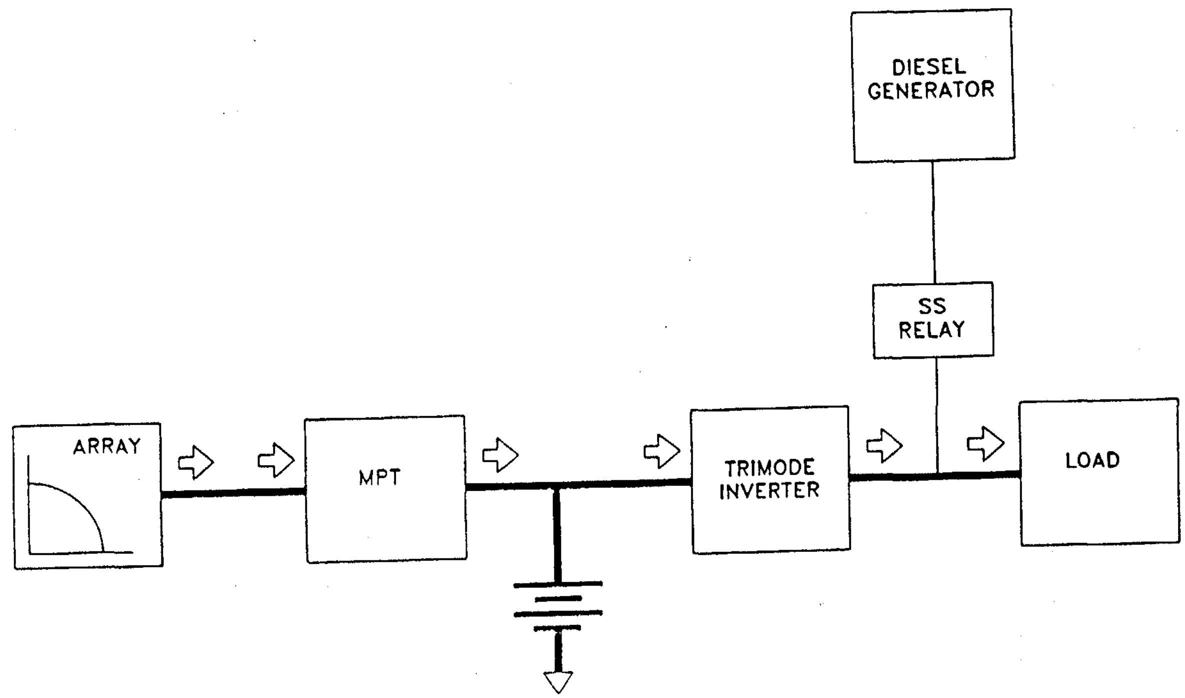



FIGURE 13
TRIMODE IN INVERTER MODE
IMPROVED DESIGN

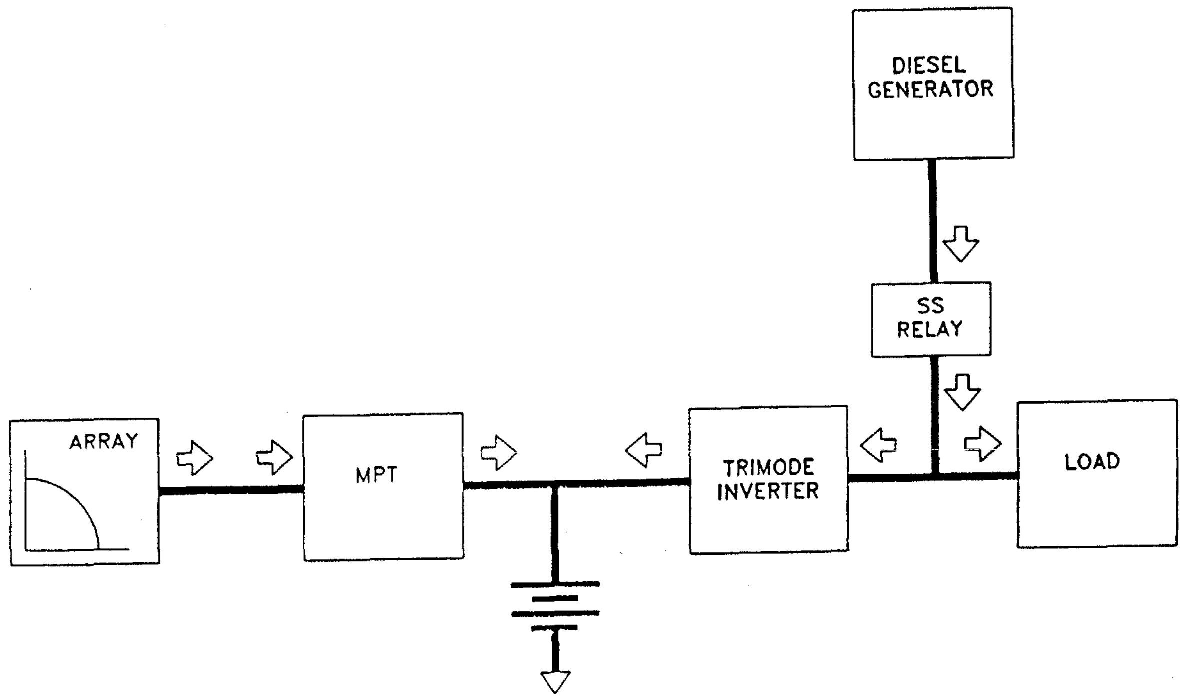



FIGURE 14
TRIMODE IN BATTERY CHARGER MODE
TRIMODE IN BATTERY EQUALIZE MODE
IMPROVED DESIGN

Figure 13 shows the Trimode in the Inverter Mode with the parts no longer required removed. Likewise, Figure 14 is the revised configuration for the Trimode both in the battery charger mode and in the equalize mode. The difference between these two modes is simply a change in the feedback arrangement as shown in Figure 12 and described above.

## TASK 4 SANDIA TEST PROGRAM

As reported above, the U S Park Service awarded Abacus a contract for a 30-kW Trimode for service in the Channel Islands. Abacus management recognized that if this unit were used for the Sandia tests in Task 4, then the budget to build a three phase Trimode for testing could serve a better purpose with reallocation to other development tasks. The U S Department of Energy Project Manager was contacted to obtain permission to test the Model 639-4 being built for the Park Service, and after permission was granted, the U S Park Service Technical Representative was contacted to obtain permission to test its unit at Sandia. Permission was granted.

The Abacus Controls development testing and the Sandia development testing on the Model 639-4M2 Trimode PCU were completed in November 1996, and the unit was delivered to the U S Park Service for installation at Channel Islands, California. The development testing took longer than the original estimates; the problems that were encountered at Sandia could not have been found at Abacus, and therefore the test program at a well equipped test facility was worthwhile.

For every problem and component failure found at Sandia, a technical explanation was derived and proven, a design change was instituted, and a retest was made to prove that the problem was resolved. This is the nature of research -- repeat and search for the best solution. The engineers at Abacus are truly proud of the test results. Dr. Russ Bonn and his Sandia team are to be commended for their support.

The Model 639-4-240 Trimode was delivered to Sandia in early August, and testing commenced on August 16, 1996. After connections between the Sandia equipment and the Trimode were verified, transfer between diesel-generator operation and inverter operation were attempted, and a serious problem was identified.

The failures at Sandia occurred at the transfer from diesel-generator with the Trimode in the battery charger mode to diesel-generator off with the Trimode in the inverter mode. In inverter terminology, this is a change from LINE-TIE to STAND-ALONE. During this transition, the Trimode reduces the power supplied by the diesel-generator from rated power to zero in thirty-two equal steps at four-second intervals. In the final step, the diesel-generator is disconnected from the load and the Trimode by turning off the solid state relay in each phase. All of the failures were tied to the final step.

Figure 15 shows the instantaneous change in control command at transfer from line-tie to stand-alone for all three phases. The time base in Figure 15 is 5 milliseconds per box. Prior to the transfer, the reference is in the current mode and is asking for 1/32nd of the diesel-generator rating from the diesel-generator. At the reference transfer in the middle of Figure 15, the reference in the stand-alone mode is the inverter output voltage. The transfer on all three phases is simultaneous.

The solid state relay transfers, as shown in Figure 16, are set at zero cross points for each phase voltage. Figure 16 is on the same time base as Figure 15; examination of the two figures together reveals that the phase A solid state relay transfers at the same time as the reference, the phase B solid state relay transfers 300° or 13.9 milliseconds after the reference change, and the phase C solid state relay transfers 60° or 2.8 milliseconds after the reference change.

There were no failures in phase A, one in phase C, and several in phase B. It was tentatively concluded that the failures are associated with the difference in transfer times for the reference and the solid state relays.

The mechanism of the failure was that, while still in the line-tie mode, a maximum current was being called for from phases B and C for a fraction of a cycle prior to transfer. The Trimode, diesel-generator and connected load were unable to react to the transient phenomenon in a timely manner.

At Abacus, the testing was not done in an isolated system with a diesel-generator and dedicated load but rather into the utility line, where the connected load was infinite compared to the capacity of the Trimode. The momentary increase in load was readily absorbed in the utility distribution system.

The corrective action was to change the solid state relay transfer in phases B and C to be simultaneous with the transfer in phase A. The results are shown in Figures 17 and 18. Figure 17 shows the phase- C transfer for the reference for both the transfer from line-tie to stand-alone (upper picture) and the transfer from stand-alone to line-tie (lower picture).

Figure 18 shows the same events as Figure 17 for the actual current from the Trimode with a substantial load connected.

Testing resumed at Sandia on September 17, 1996. Significant test results were reported by Jerry Ginn, Sandia Test Engineer, and they are included here under the title "Channel Islands Hybrid Design," Figure 19. A 12.8-kW load is connected to the system and is identified in the figure by a dotted line. From the left, first there is a transfer from diesel-generator to inverter, then a transfer from inverter to diesel-generator.

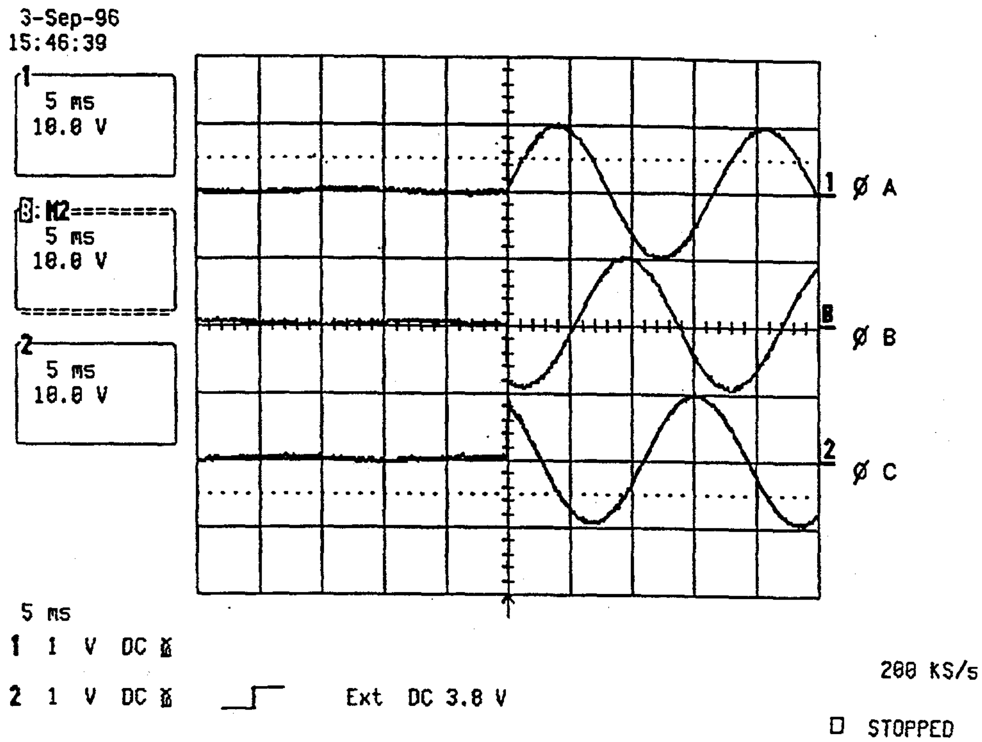



FIGURE 15
REFERENCE TRANSFER
LINE TIE TO STAND-ALONE

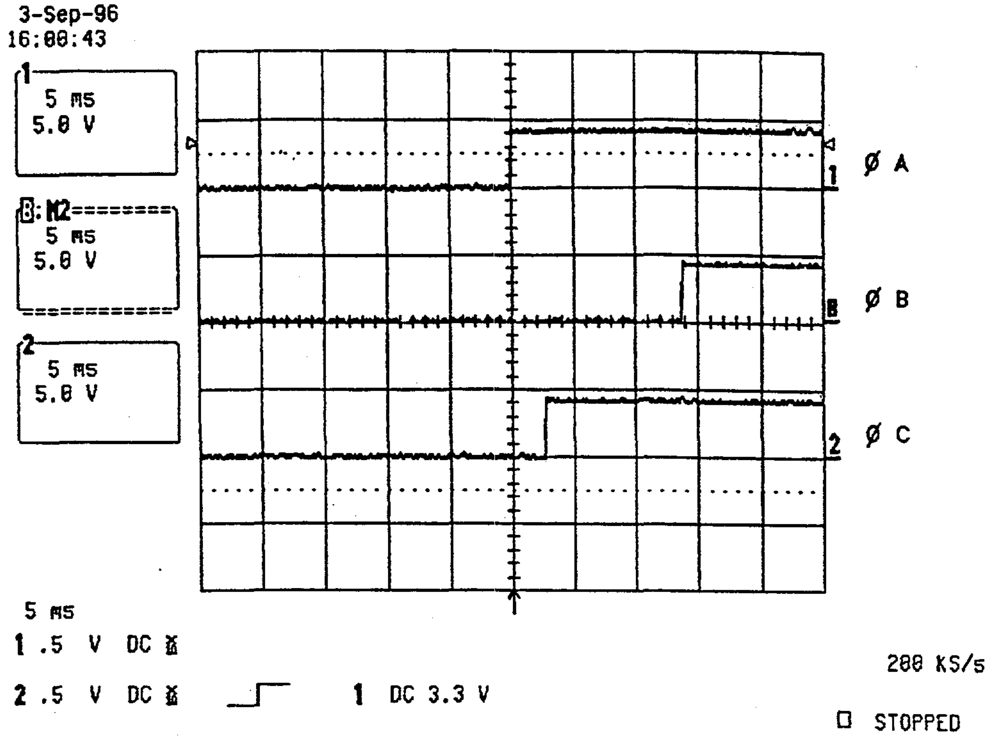



FIGURE 16
SOLID STATE RELAY TRANSFER
AT ZERO CROSS

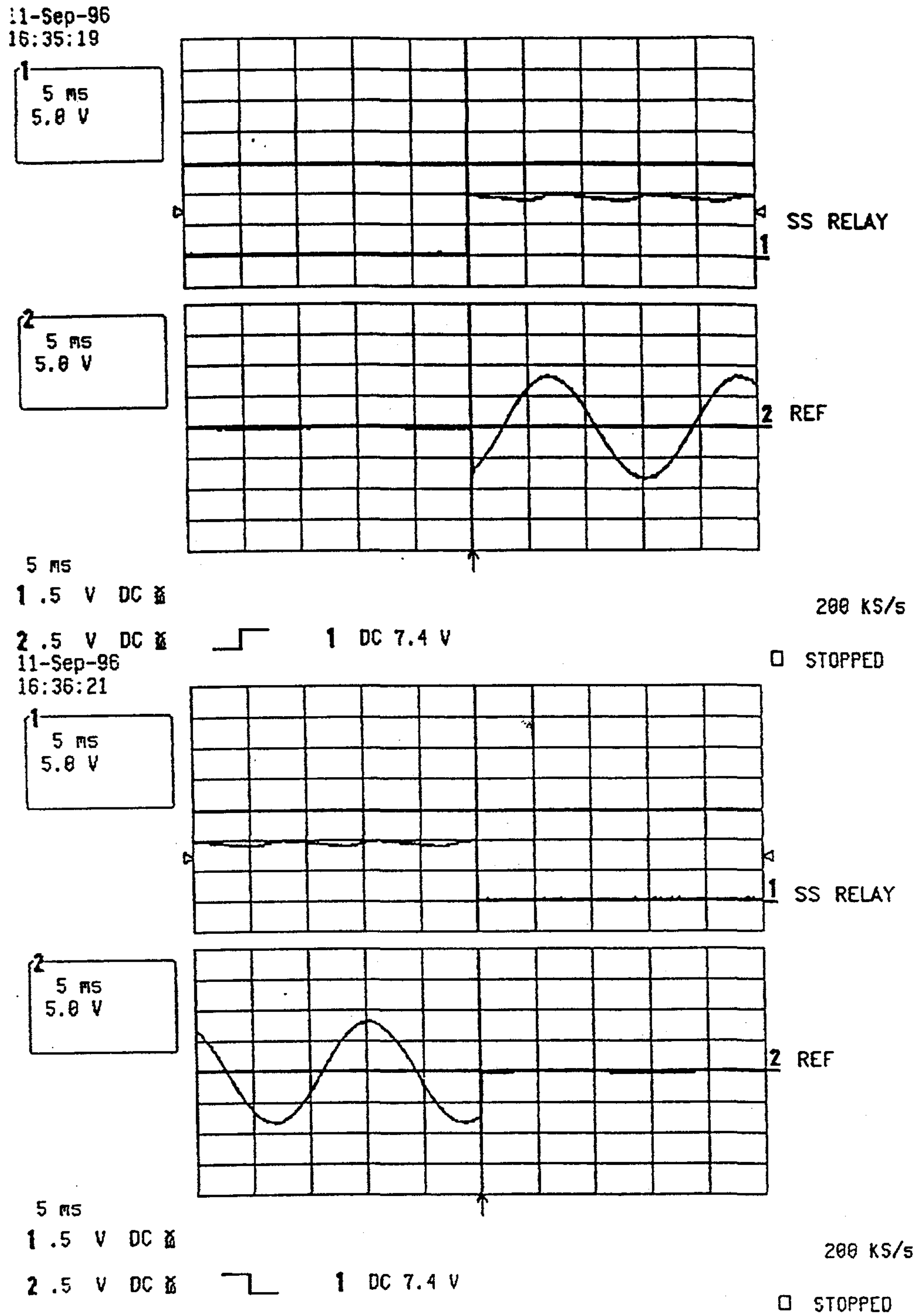



FIGURE 17 PHASE C TRANSFER (REF)

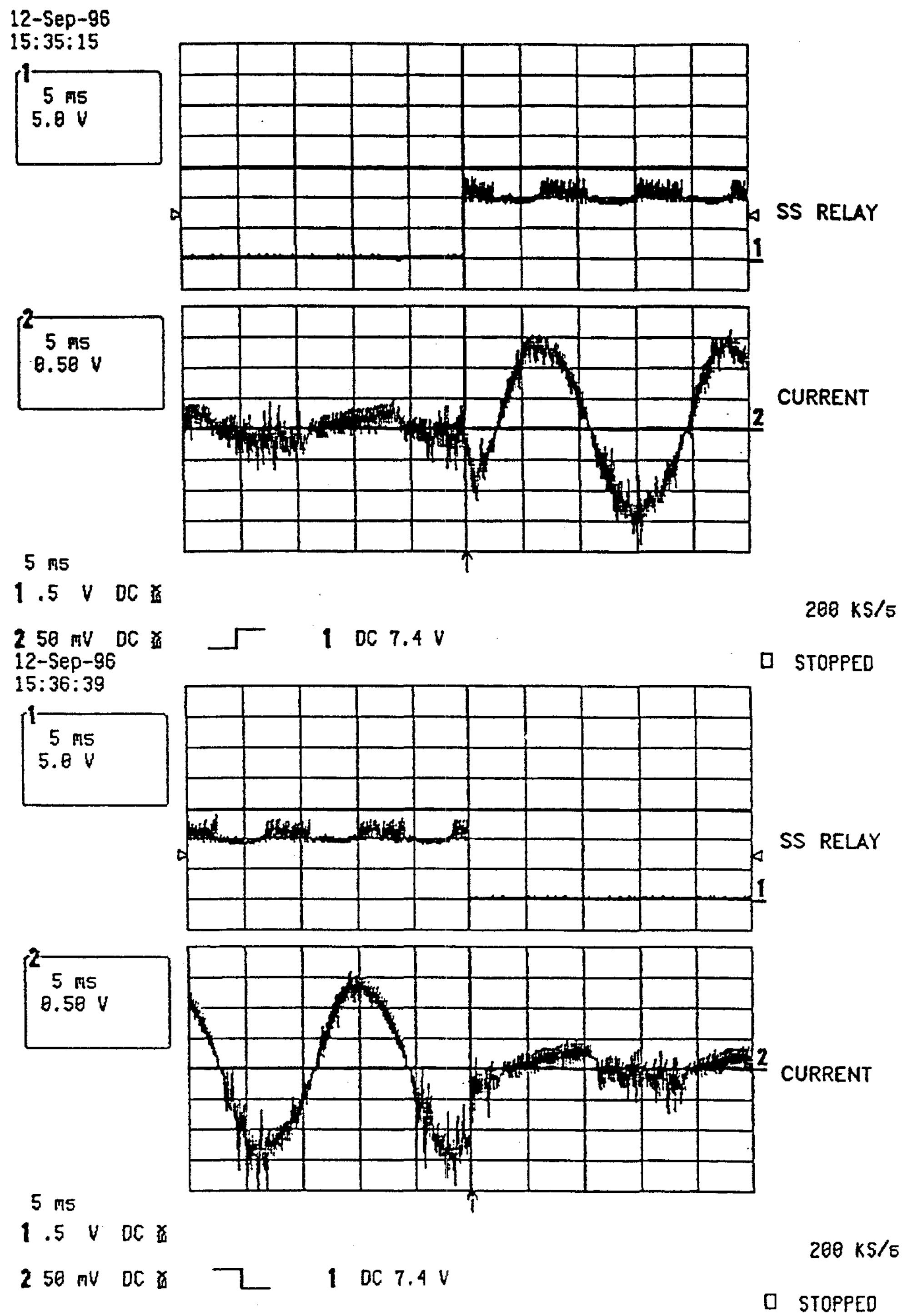



FIGURE 18 PHASE C TRANSFER (ACTUAL I)

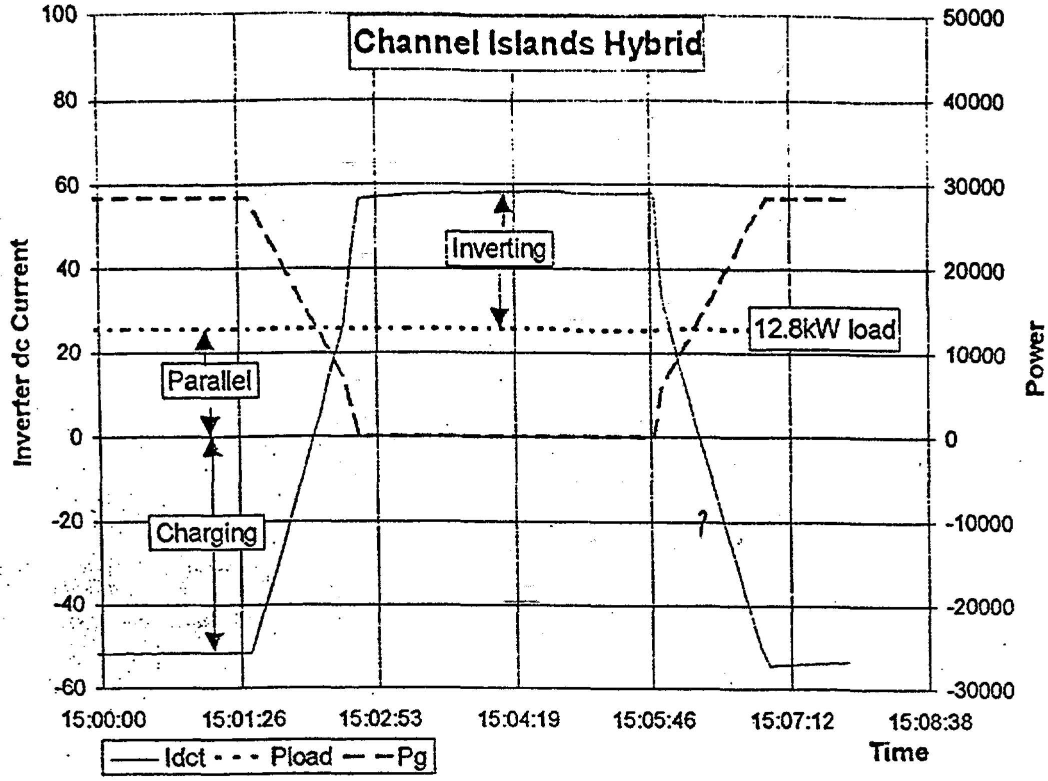



FIGURE 19
BUMPLESS TRANSFERS BETWEEN
TRIMODE AND DIESEL

In the diesel-generator mode (see Figure 5 for the system configuration) the battery is being charged at 52 amperes (minus 52 amperes in the figure). With the scale on the right, the diesel-generator power, the dash-dash line, is 28 kW. Note that the time scale is approximately 1 minute 26 seconds per box.

The transition starts, with 32 steps, 3 seconds each. The battery charge current decreases through zero as the diesel-generator power decreases. When the battery current crosses through zero and the diesel-generator power crosses through the load power line, the Trimode transitions from battery charge to operating in parallel with the diesel-generator.

When the diesel power reduces to zero at the end of the 30-second step, the solid state relay opens, the diesel-generator is disconnected from the system, and the Trimode supplies the load from the battery by drawing a positive 57 amperes.

The reverse transition from inverter in stand-alone to line tie and then battery charge is the mirror image of the forward transition. The solution to transfer all three solid state relays at the same time as the reference change has solved the problem.

Four data curves that illustrate the Trimode state-of-the-art performance at Sandia are described below. With the generator turned on, the Trimode regulates the current from the generator to be constant at full rated power and in phase with the generator voltage.

Figure 20, "Channel Islands Generator Support", shows the laboratory tests for a condition where the generator power held constant for increases in load power from 0 kW to 55 kW. Both the generator and the Trimode are rated at 30 kW. At 0 kW load, the Trimode charges the battery with 27 kW. When the load power exceeds the power rating of the generator, the Trimode automatically changes from battery charging to line-tie inverting and adding power to the generator power. In Figure 20, this appears as negative battery charge power.

Figure 21, "Channel Islands Transfer & Begin Equalize", shows shows the laboratory tests for a condition where the Trimode transfers smoothly from the inverter mode to equalize when the equalize push button is depressed at 7:30. The Trimode charges the battery to 278 V, then transfers to the max power tracker (MPT) for a constant voltage charge for an operator settable period of time. The generator supplies the load during equalize.

The remaining data curves are on a per cycle basis. Correction of power factor to minimize generator fuel consumption is depicted in Figure 22. A 10-kW load at 0.5 power factor is applied to all three phases of the Trimode and generator. The actual current supplied by the generator, Iga in Figure 22, is at a power factor of .997, phase angle of 4.2°.

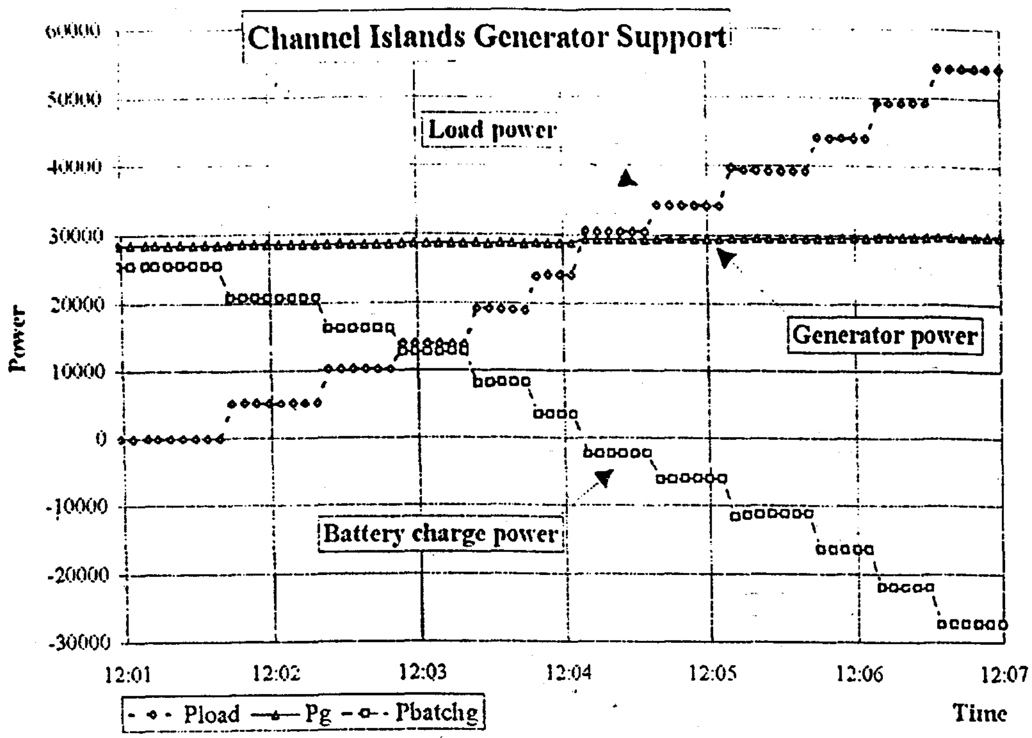



FIGURE 20
GENERATOR SUPPORT

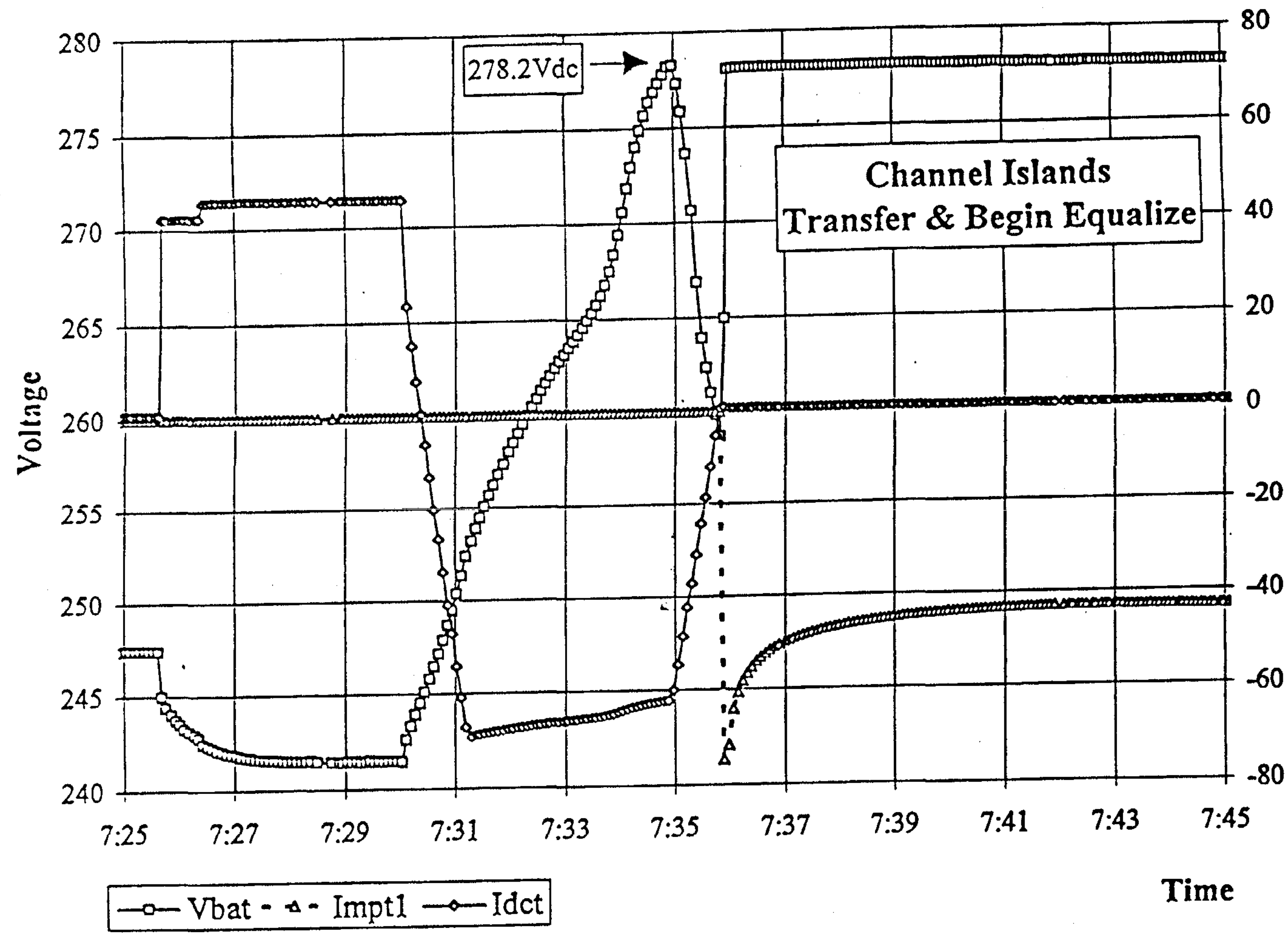



FIGURE 21 TRANSFER FROM INVERTER MODE TO EQUALIZE

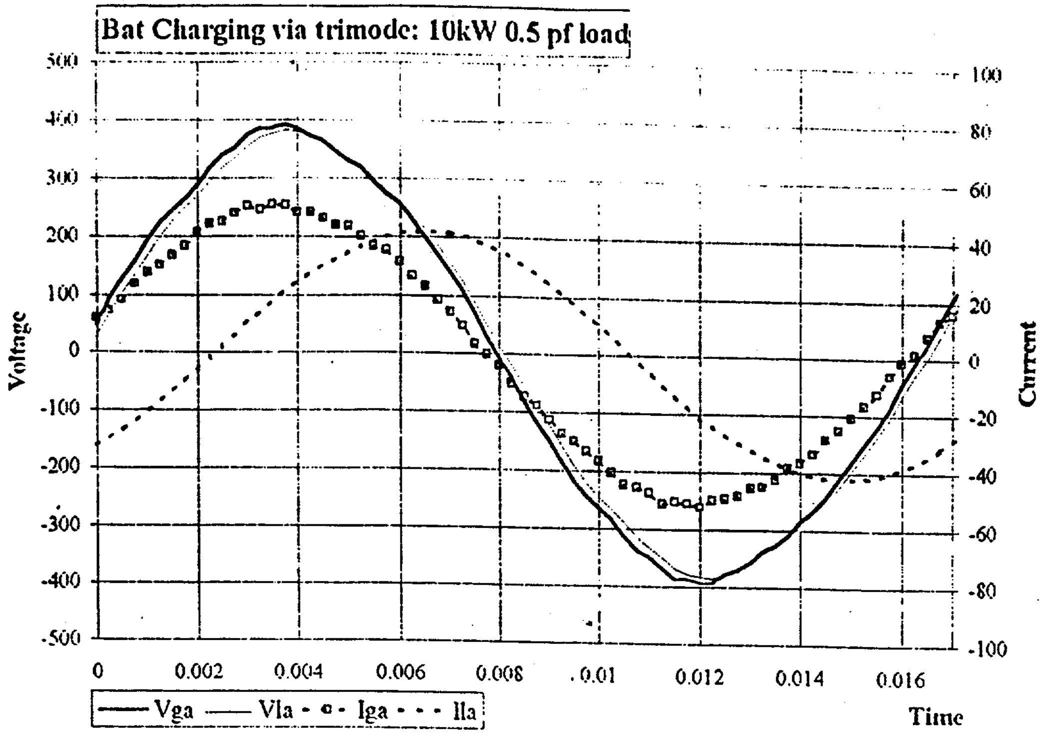



FIGURE 22
POWER FACTOR CORRECTION

### Correlation of Test, Design and Simulation

Figure 23 shows the Trimode and generator with a 4.6-kVA nonlinear load on phase A only. Note that the Trimode works on a per phase basis. The THD of the nonlinear current, Ila in Figure 23, is estimated to be at least 150%, the third harmonic alone exceeding 100%. With the Trimode regulating the current on a sub-cyclic basis, the generator current, Iga, approaches being a sine wave. The measured THD of the load voltage was 2.5%.

During the Phase I effort under the subject U S Department SBIR Grant, design, prediction and simulation were completed. Figure 24 shows the design goal for the Trimode and diesel-generator currents due to a non-linear load. The design goal is that 100% of the non-linear load current will be absorbed by the Trimode, leaving the diesel-generator supplying a perfect sinewave current.

The simulation results, shown in Figure 25, show a close correlation with the actual observed current in Figure 23. The conditions are not the same, so a quantitative comparison cannot be made; but the qualitative comparison shows the same general waveshape, especially the response to the end of the non-linear current pulse.

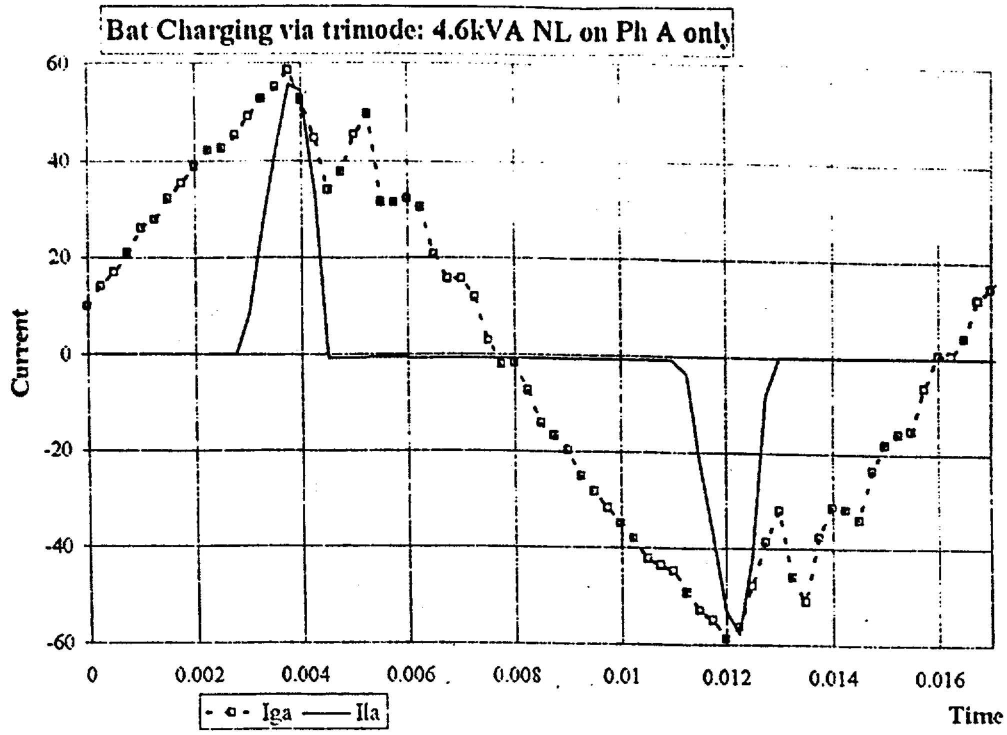
## TASK 5 THREE-PHASE 300-kW TRIMODE

An early start on the PQE controller design for village sized systems was partially motivated by two recent publications.[2 3] The significant feature is the application of different switching patterns to two or more inverter bridges. Adaptation to the PQE controller for high power applications, where more than one inverter is required per phase, will increase efficiency, reduce harmonic content and double the speed of response without an increase in cost.

Abacus used the "different pattern" technology with Sunverters in the 1980's, but the technique has not been applied to the sampled-data type controller. The application, as well as the anticipated results, will be unique to the PQE Controller.

Figure 26, Trimode dual bridge wave shapes, illustrates the theory of the application. The first waveshape in Figure 26 is a 192 step sinewave reference, which is compared to the output to generate an error signal. Each bridge acts on every other pulse, and the combination of the two bridges is added by the series connection of the bridge output transformer secondary windings.

The second waveshape on the figure is the first bridge pulse pattern with 96 steps per cycle. The third waveshape is the second bridge pattern, which is displaced by 1.875 degrees from the first bridge waveshape. The fourth waveshape is the linear addition of the first bridge and second bridge pulse patterns. Note that in the individual bridge patterns, three voltage




THD in the load voltage at this time was 2.5%.

FIGURE 23
NON-LINEAR LOAD CORRECTION

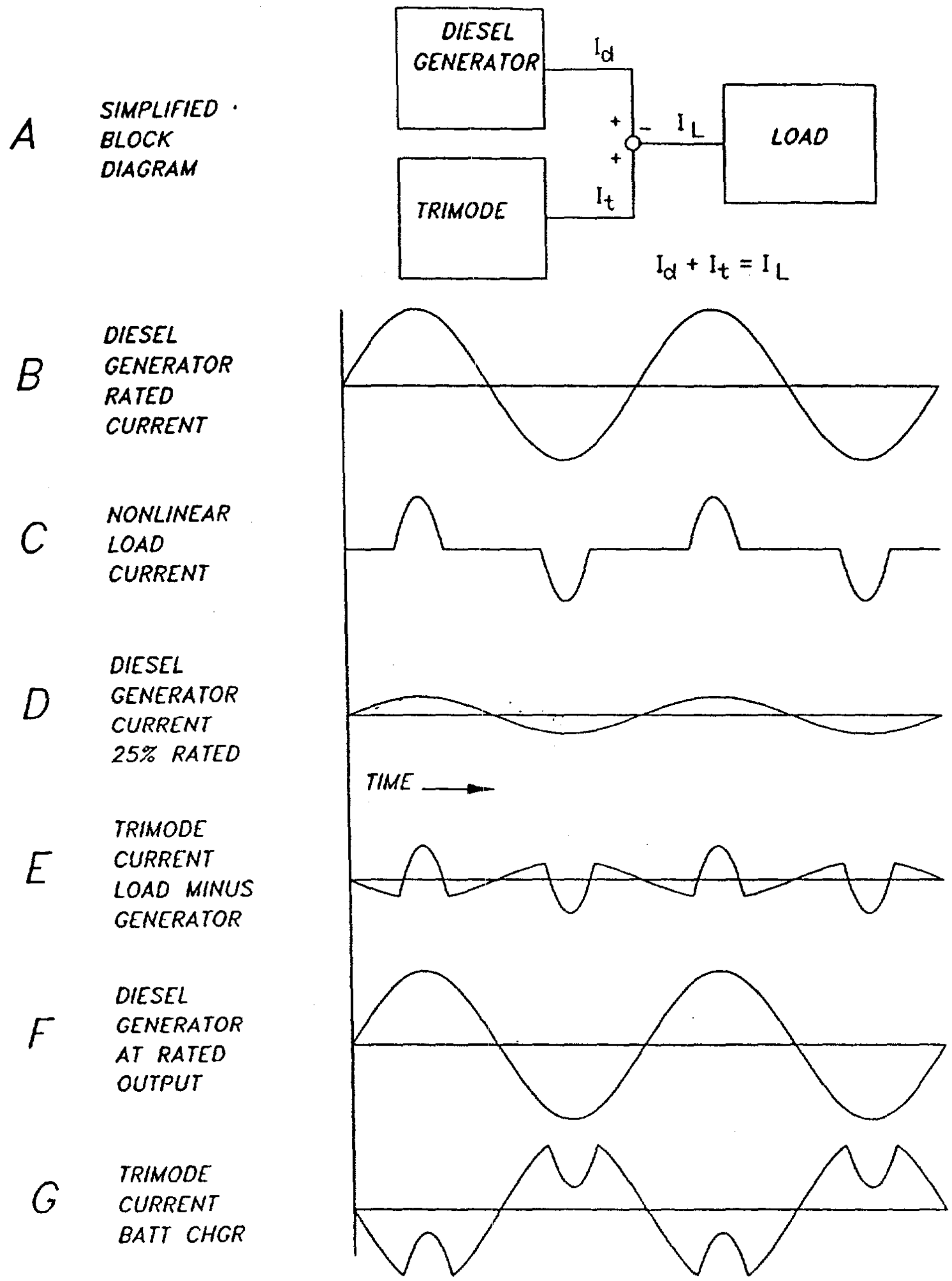



FIGURE 24
POWER QUALITY ENHANCEMENT

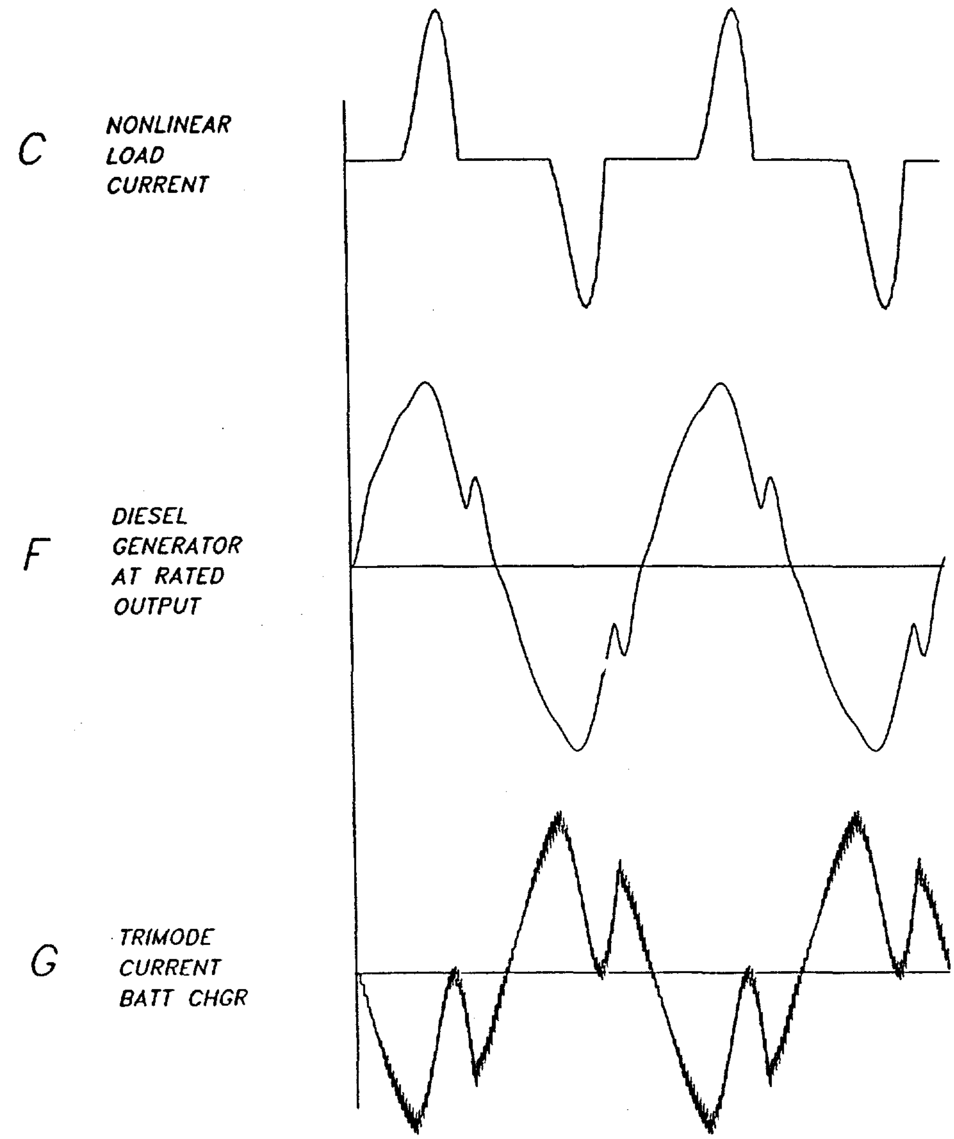



FIGURE 25
SIMULATION AT RATED OUTPUT
POWER QUALITY ENHANCEMENT

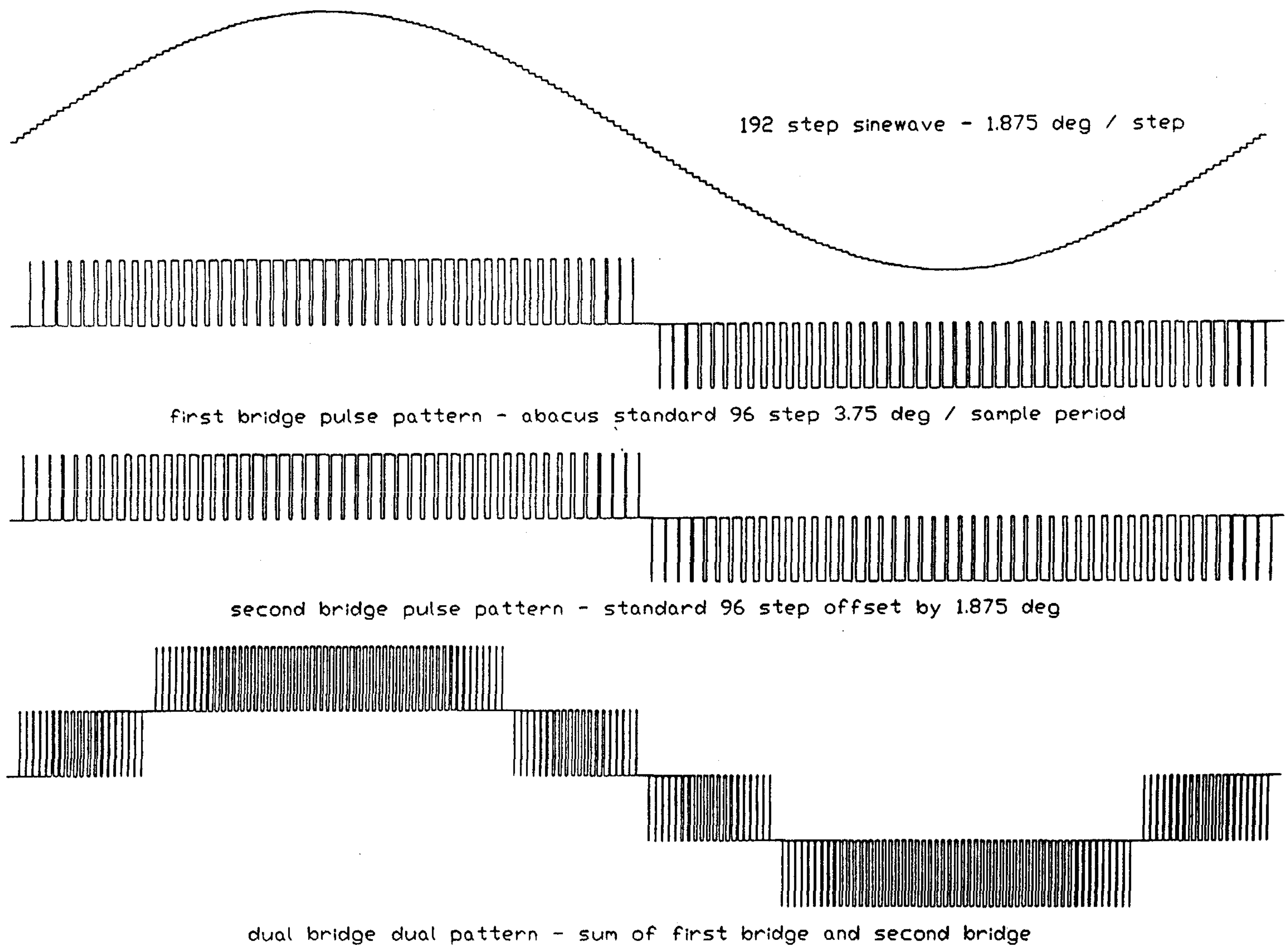



FIGURE 26 TRIMODE DUAL BRIDGE WAVESHAPES

levels exist. For the sum of bridge pulse patterns, five voltage levels exist. See Appendix A for a derivation of the control equations for the dual bridge design.

In sampled-data controllers the pulses grow wider from the center, so after the individual pulse widths exceed 50% of each period, one of the two bridges is positive (negative in the negative half cycle) at all times. Thus the five voltage levels are created, the harmonic content is reduced, efficiency is increased because each bridge is switching at only half the sample frequency, and, after the non-recurring design costs are covered, the cost will be decreased because of the reduced filter requirements for the five step waveshape.

Programming an ASIC for the dual pattern PQE Controller was completed as the next step in the research and development of a village scale Trimode Power Processor. The method used to accomplish the sending of alternate pulses to two bridges is illustrated in Figure 27, dual bridge pulse generation. The top wave shape is the error amplifier output with 192 samples per cycle. Each bridge operates on every other pulse, with properly arranged sampling and triangle waves. Theses are shown in the second and third wave shapes.

Where the step waves cross the triangle waves in the first bridge and the second bridge samplers, pulses are created, and these are shown in the figure with vertical dashed lines. Where one pulse exists, the bottom wave shape, sum of first bridge and second bridge pulses, is at level 1. Where two pulses exist, the output is at level 2.

Laboratory tests on a single phase model of the dual bridge demonstrate the expected results. Figure 28 shows the generated 192 step sine wave. Figure 29 repeats the sine wave along with the dual bridge patterns summed on an oscilloscope. The dual patterns are a full wave rectified version of the output prior to distribution to the proper IGBT's in the output bridges.

A single phase production unit, Model 443-4-48, a 48-VDC Inverter for stand-alone PV applications, was also tested with the dual bridge to prove stability (see Appendix A) and design accuracy in predicting the reduced filter requirements. Performance was better than expected, with the output voltage from no load to full load and input voltage changes from 38.4 VDC to 57.6 VDC producing an output voltage of 120 VAC ± 0.8 VAC with a THD < 1.5%.

Figures 30 and 31 demonstrate the additive property of the dual bridge when the transformer secondaries are connected in series. Balance is more precise with transformer secondaries in series rather than in parallel; in series, the current is the same and the voltages are the contributions of parallel inputs operating from the same DC source, whereas the in parallel, the voltage is the

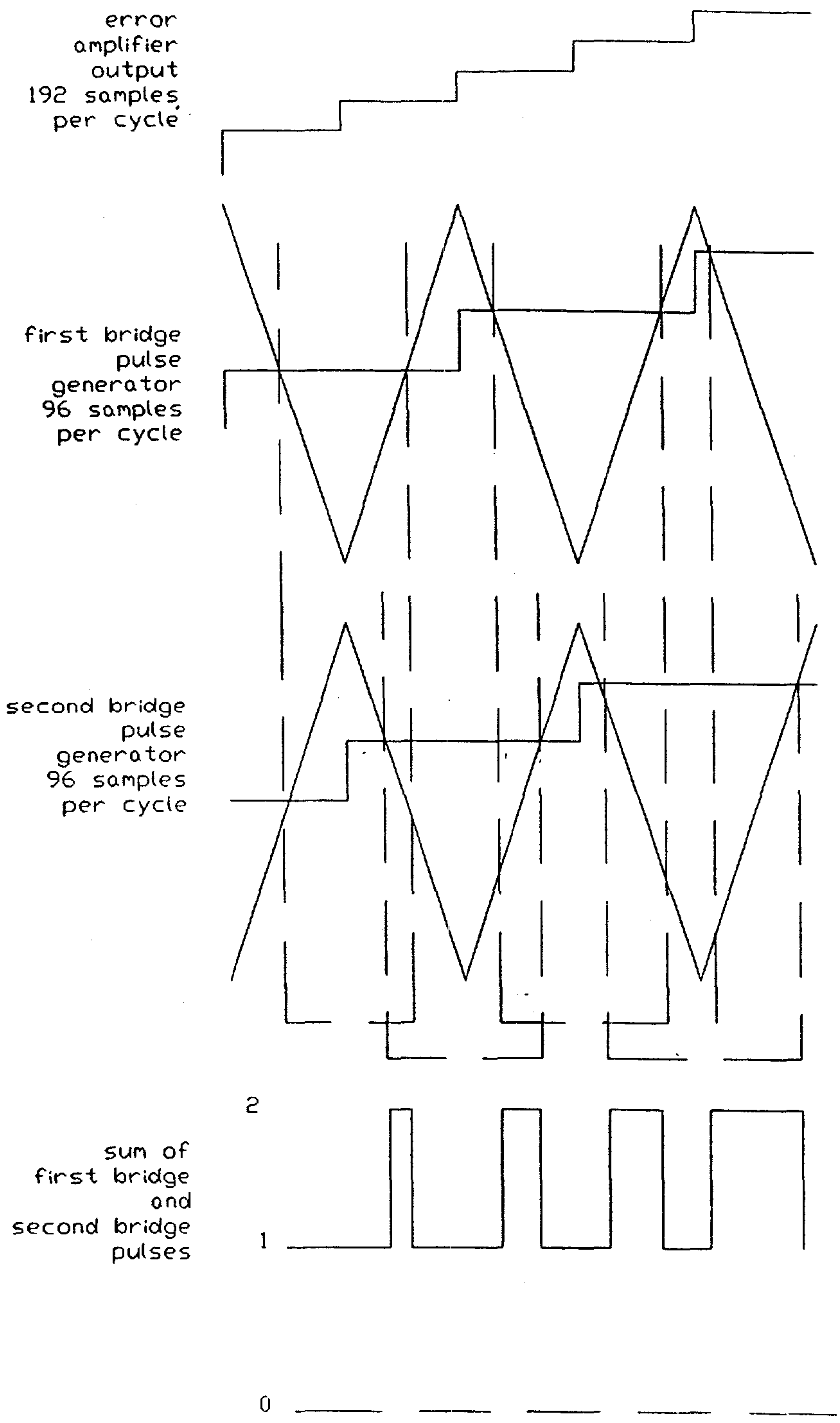



FIGURE 27 DUAL BRIDGE PULSE GENERATION

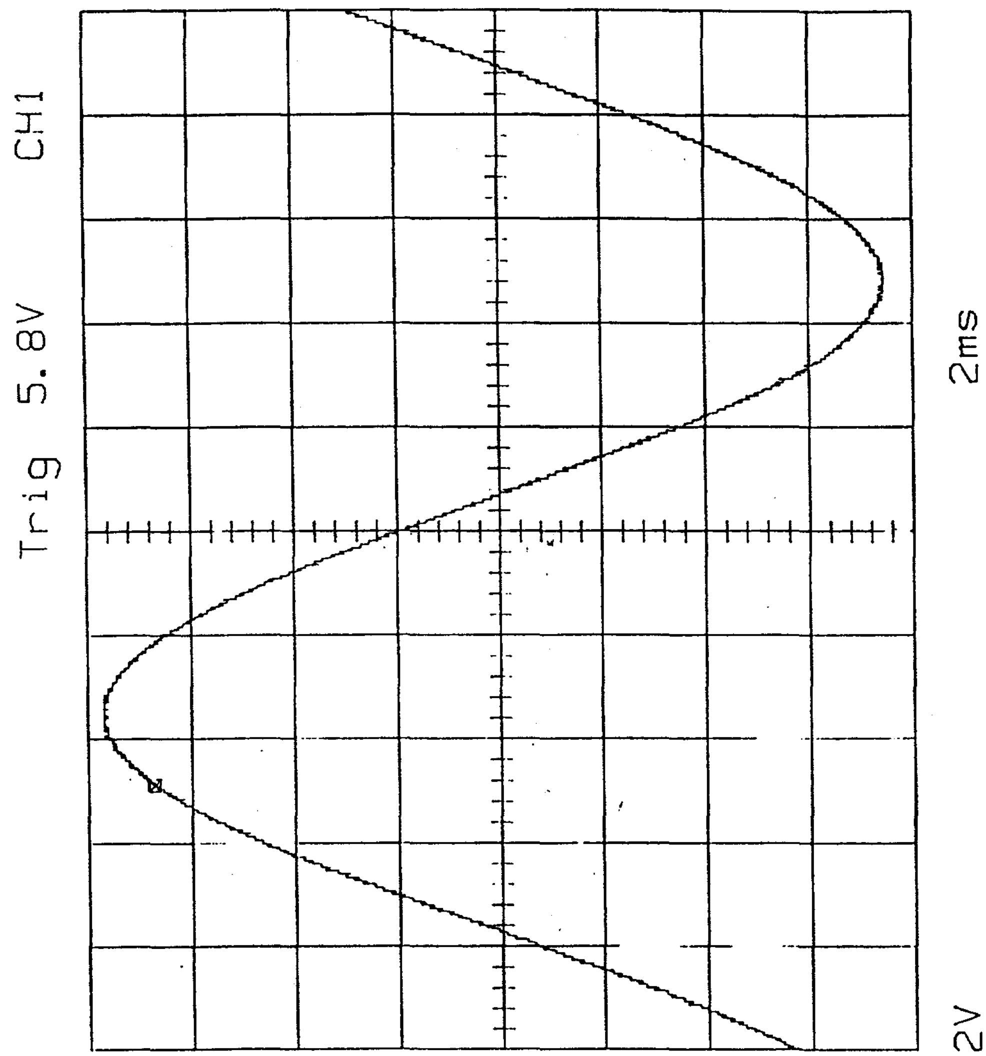



FIGURE 28 192 STEP SINEWAVE

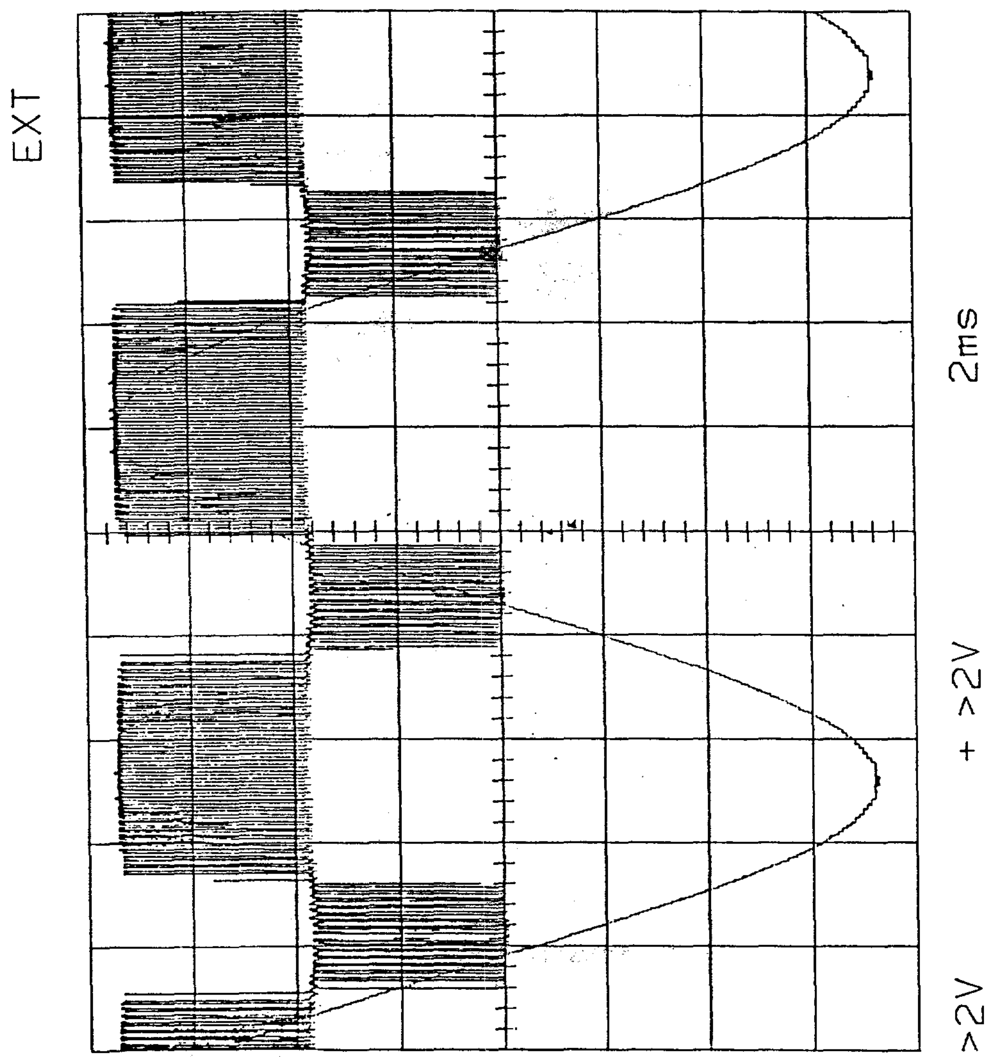



FIGURE 29
DUAL BRIDGE PATTERNS SUMMED

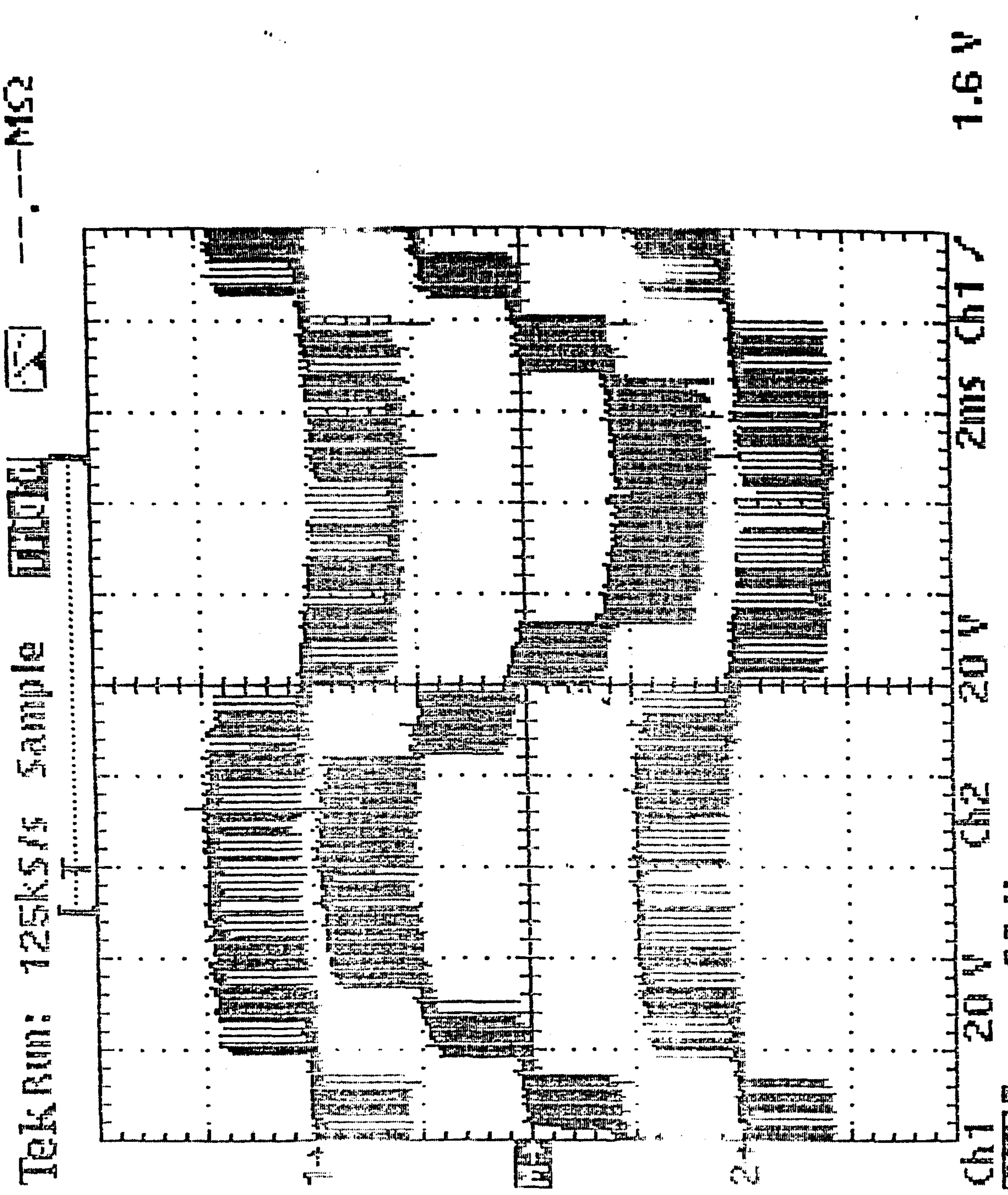



FIGURE 30
DUAL BRIDGE OUTPUT PULSE PATTERNS
2ms Timing

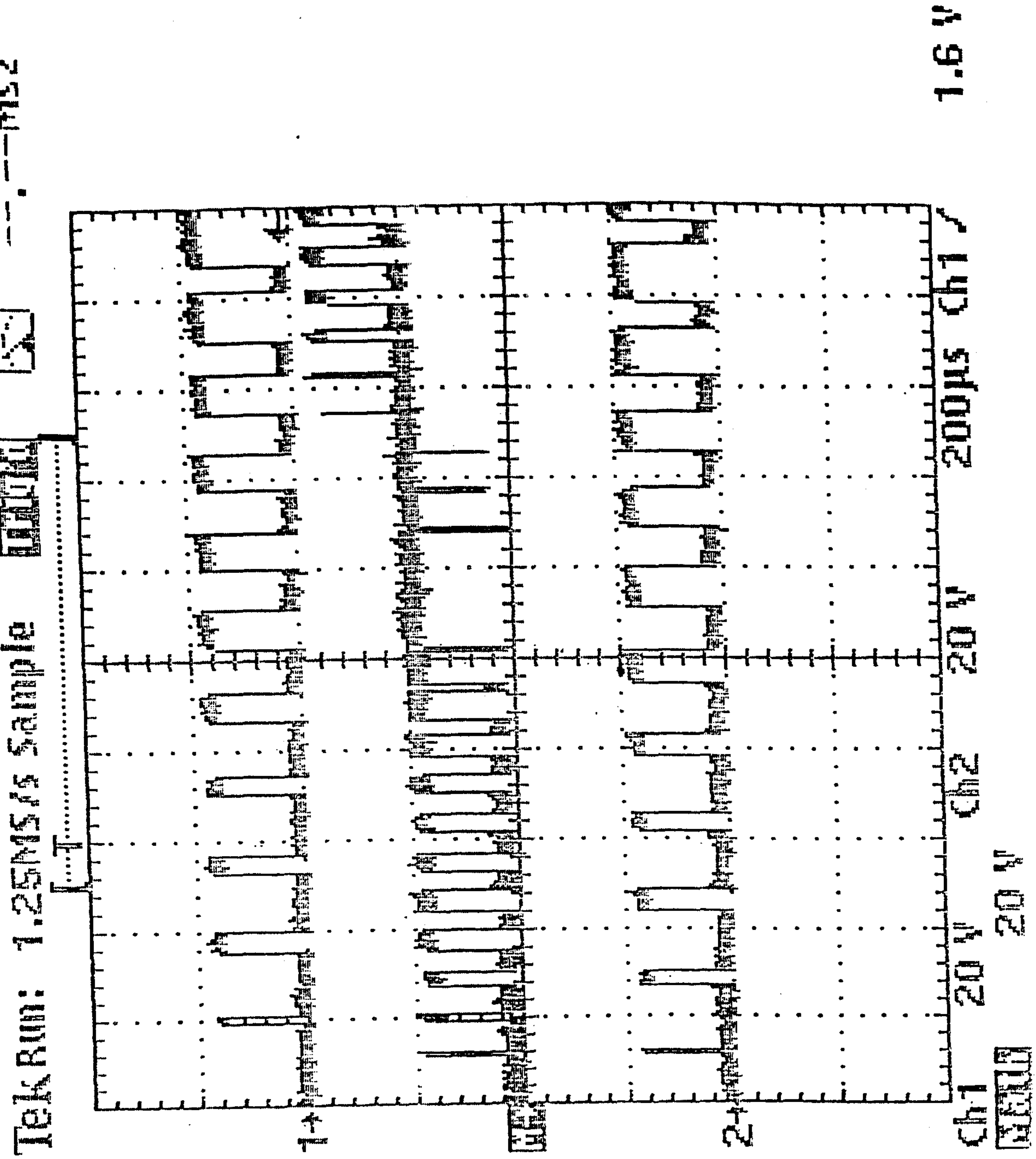



FIGURE 31
DUAL BRIDGE OUTPUT PULSE PATTERNS
200ms Spacing

same but the currents are dependent on many parameters, whose tolerances are difficult to control.

Figure 30 shows the dual bridge output patterns with 2 ms timing. Isolated scope inputs were connected across the primary of each transformer (traces 1 and 2), with the sum shown in the middle (trace M). Figure 31 is for the same connection and operating conditions with the timing set at 200 μsec. The expected transition from positive level one to positive level two can clearly be seen.

## TASK 6 MICROCONTROLLER DISPLAY DESIGN

As part of the redistribution of funds made possible by delivering a Trimode to Channel Islands, a microcontroller, coupled with a key pad and a display, has been designed into the Trimode. The microcontroller selected for this purpose is the Intel 87C51FA m icrocontroller. As part of the MCS 51 microcontroller family, this device offers future opportunities for upgrade as the need arises. The particular device selected has 8kB EPROM and 256 B RAM. It has four 8-bit bidirectional parallel ports, three 16-bit timer/counters, a full-duplex programmable serial port, an interrupt structure, and power-saving modes. This is sufficient for the present application. One crucial feature is that it has EPROM. This is crucial because many of the Trimode units have custom features that can be programmed into individual units. It is also important for the initial firmware development.

A 2-by-16 LCD display has been chosen. This display will allow information about alarm conditions or requested status information to be displayed. The requests are made through the key pad on the unit. For a key pad, a standard telephone style key pad has been chosen. A National Semiconductor MM74C922 16-key encoder chip has been chosen to provide the logic to encode the key pad input into a format readable by the microcontroller.

Figure 32, control panel layout, shows the silkscreen for operator instructions for CONTROL, STATUS, and METER SELECT. This user-friendly guide is backed up with instructions on the LCD display should an improper set or order of key strokes be used. The control commands are:

| | | |
|---|---|---|
| * 0 | AUTOMATIC | normal operation |
| * 1 | INVERTER | startup, diesel maintenance |
| * 2 | GENERATOR | Trimode maintenance |
| * 3 | EQUALIZE | equalize charge the battery |

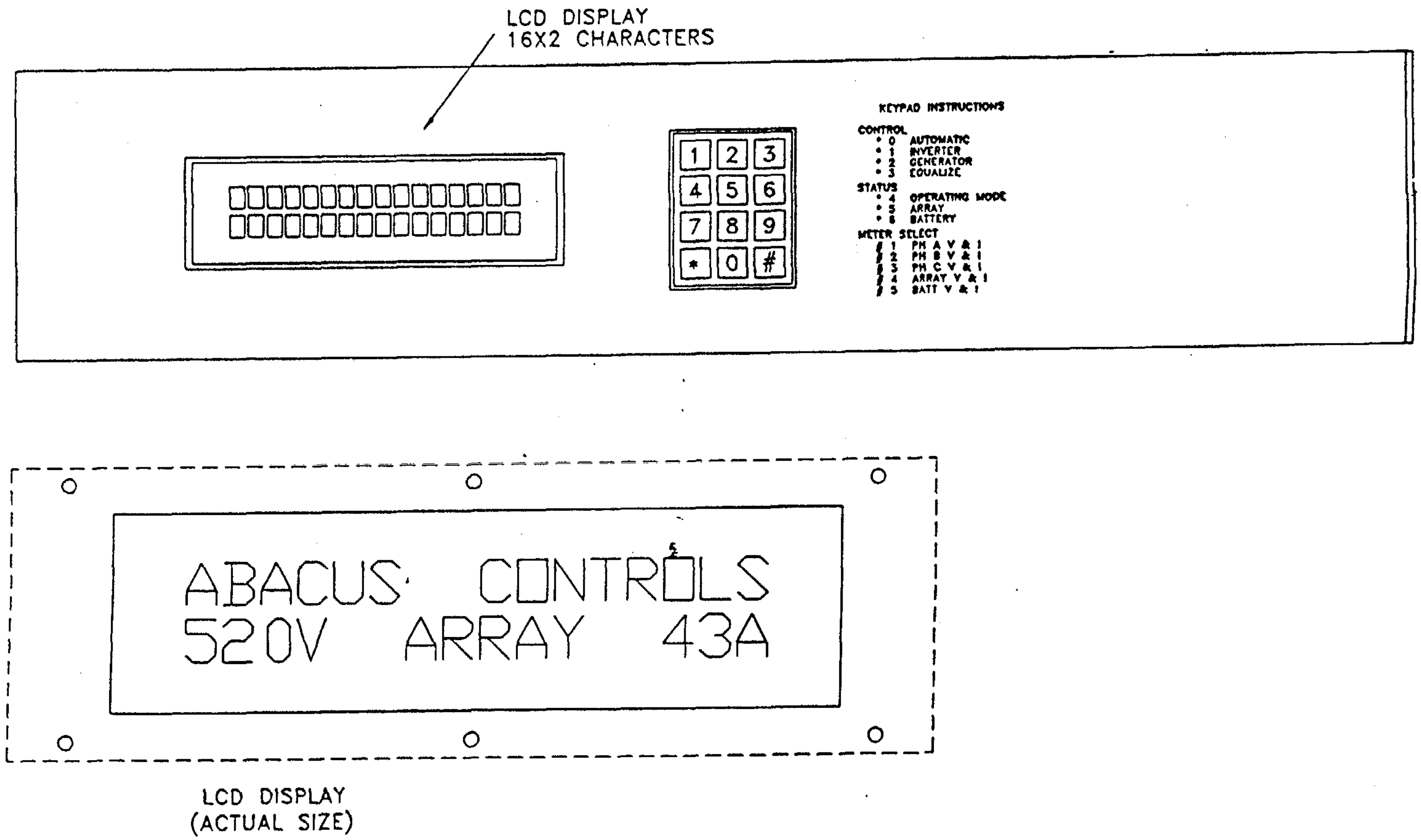



FIGURE 32 CONTROL PANEL LAYOUT

The status commands and options are:

| | | |
|---|---|---|
| * 4 | OPERATING MODE | AUTOMATIC / GENERATOR ON<br>AUTOMATIC / GENERATOR OFF<br>INVERTER<br>GENERATOR<br>OFF |
| * 5 | ARRAY | ACTIVE<br>LOW VOLTAGE |
| * 6 | BATTERY | DISCHARGING<br>CHARGING<br>IDLE |

For meter select, both volts and amps are displayed. The array meter select appears as an insert in Figure 32. Battery current polarity is + charging, - discharging.

| | | |
|---|---|---|
| # 1 | PH A | V & I |
| # 2 | PH B | V & I |
| # 3 | PH C | V & I |
| # 4 | ARRAY | V & I |
| # 5 | BATT | V & I |

Alarms that will be automatically displayed on the LCD display are:

| | |
|---|---|
| BATTERY OVERVOLTAGE | BATTERY UNDERVOLTAGE |
| DIESEL OVERVOLTAGE | DIESEL UNDERVOLTAGE |
| INVERTER OVERVOLTAGE | INVERTER UNDERVOLTAGE |
| FREQUENCY ERROR | LOSS OF PHASELOCK |
| OVERLOAD | OVERTEMP |

## SMART POWER APPLICATIONS

The modular design in the Abacus Trimode Power Processor lends itself to incorporating design improvements in the driver stages and in the power stages. Recent advances in "smart power" have taken place at low power by International Rectifier and at high power by Toshiba.

International Rectifier has made a significant breakthrough in smart power technology with the introduction of a family of MOSFET power switches that can be driven directly from ASIC outputs. A typical data sheet for the IR6226 is included with this report. Abacus intends to take full advantage of this new component to
reduce cost and improve reliability in low power PV applications.

In March 1997 Toshiba released its "Intelligent GTR Module" product family, which covers IGBT's from 20A to 200A, both single and dual. Protective features include over-current, short circuit, over-voltage, under-voltage, over temperature, bias supply under-voltage, and fault output pulse width. Switching times are still a problem, 4 μsec turn-off versus 0.5 μsec for the IGBT's currently being used.

## APPENDIX A

## 192 PULSE DERIVATION FOR TWO BRIDGES

For use with two bridges per phase, the 192 pulse pattern is designed to have switching losses no greater than the 96 pulse pattern. This is accomplished by switching each transistor pair every other sample period.

The derivation is best described for the single phase version, as shown in Figure 26, TRIMODE DUAL BRIDGE WAVE SHAPES. There are two H-bridges whose outputs are connected to the primaries of two transformers. The secondaries are connected in series. Let $v_1(t)$ and $v_2(t)$ denote the two voltages on the secondaries and let $v_L(t)$ denote the voltage across the load. Using upper case letters for Laplace transforms, we have

$$V_1(s) + V_2(s) - V_L(s) = sL\, I(s),$$

where i(t) is the current in the inductor. The load voltage is related to the inductor current by

$$V_L(s) = \frac{RI(s)}{1+sRC} = \frac{V_1(s) + V_2(s)}{s^2+s/RC+1/LC} .$$

The optimal control scheme used is a modification of the dead beat control strategy.[1,2,3,4,5] The derivation starts with a state space description for the system, given by

$$\frac{d\mathbf{x}}{dt} = A\,x + B\,(v_1(t) + v_2(t)),$$

$$v_L(t) = [1\ 0]\,\mathbf{x}(t),$$

where

$$x(t) = [v_L\ \ dv_L/dt]$$

and

$$A = \begin{bmatrix} 0 & 1 \\ -1/LC & -1/RC \end{bmatrix} \qquad B = \begin{bmatrix} 0 \\ 1/LC \end{bmatrix}$$

This continuous time description is transformed into a discrete time system by computing the load voltage at the next sample instant in terms of the present value and the input voltages:

$$\mathbf{x}[(k+1)T] = e^{AT}\,\mathbf{x}(kT) + \int_{Kt}^{(k+1)T} e^{A((k+1)T-\tau)}\,B\,[v_1(\tau) + v_2(\tau)]\,d\tau .$$

This equation is used to find the values for the switch durations of the two input bridges so that the predicted value equals the ideal value. The technique is modified somewhat from the standard approach, however. Only one switch duration is computed at each step, and this switch duration can go up to 2T. The top switch is computed at odd numbered sample times and the bottom switch is computed at even numbered sample times. The derivation is based on approximating the matrix exponential by the first one or two terms in its series expansion:

$$e^{AT} \approx I + AT + 0.5\,A^2T^2 ,$$

where the second term in the expansion is usually ignored also. This approximation can be used for integrals as well. The input is now separated into three terms. Let

$$u(t) = \begin{cases} 0, & \text{for } kT < t < (k+2)T - \Delta T(k+1)/2, \\ E, & \text{for } (k+2)T - \Delta T(k+1)/2 < t < (k+2)T. \end{cases}$$

Then

$$\int_{kT}^{(k+2)T} e^{A((k+1)T-\tau)}\, B\, u(\tau)\, d\tau \approx E\, \Delta T(k+1)/2 \begin{bmatrix} \Delta T(k+1)/4 \\ 1-\Delta T(k+1)/4RC \end{bmatrix},$$

where the second order terms have been ignored. Note that in this equation, the first term is the contribution to the next predicted voltage and $\Delta T$ enters this term quadratically. Thus, this term may be ignored in a first order expansion. This is important for the derivation since it implies that the next computation for the other switch duration has no first order effect on the computation under consideration. That is, if we are at an odd time, the computation is independent of the switch duration that will be computed for the even time one step into the future. The same cannot be said about the even computation one step into the past. For the effect of that computation, let

$$u(t) = \begin{cases} E, & \text{for } kT < t < kT + \Delta T(k-1)/2, \\ 0, & \text{for } kT + \Delta T(k-1)/2 < t < (k+2)T. \end{cases}$$

Then

$$\int_{kT}^{(k+2)T} e^{A((k+1)T-\tau)}\, B\, u(\tau)\, d\tau \approx \frac{E}{2LC} \Delta T(k-1) \begin{bmatrix} 2T \\ 1-2T/RC \end{bmatrix} .$$

The third and final term that arises from the switch duration computations is from the present switch duration. It is this term that dominates our consideration. Let

$$u(t) = \begin{cases} 0, & \text{for } kT < t < (k+1)T - \Delta T(k)/2, \\ E, & \text{for } (k+1)T - \Delta T(k)/2 < t < (k+1)T + \Delta T(k)/2, \\ 0, & \text{for } (k+1)T + \Delta T(k)/2 < t < (k+2)T. \end{cases}$$

Then

$$\int_{kT}^{(k+2)T} e^{A((k+1)T-\tau)}\, B\, u(\tau)\, d\tau \approx \frac{E}{LC}\Delta T(k) \begin{bmatrix} T \\ 1-T/RC \end{bmatrix} .$$

Combining these results,

$$v_L((k+2)T) \approx \left(1-\frac{T^2}{LC}\right) v_L(kT) + 2T(1-T/RC)\frac{dv_L}{dt}(kT) +$$

$$\frac{E}{LC}\, T(1-T/RC)\ \Delta T(k-1) + T\,\frac{E}{LC}\,\Delta T(k) + \Delta T(k+1)^2 \frac{E}{2LC} .$$

Again, since $\Delta T(k+1)$ enters quadratically, it may be dropped from this expression without much loss in precision. In addition, the factor (1-T/RC) is usually approximated as 1; if this approximation is not valid, it is easily incorporated in the following. This equation is used in dead beat calculations to determine the next switching duration in terms of the present output voltage, its derivative, and the reference value at the next time instant. Here, that computation yields

$$\frac{\Delta T(k)}{T} = -(1-T/RC)\ \frac{\Delta T(k-1)}{T} + \frac{LC}{ET^2}\{v_{REF}[(k+2)T] - (1-2T^2/LC)v_L(kT) -$$

$$2T(1-T/RC)\frac{dv_L}{dt}(kT)\} .$$

This ideal computation for the next switch duration depends on the previous switch duration with the factor -(1-T/RC). This factor is close to -1, making this computation, when viewed as a filter, close to being unstable. If this were to be implemented directly, it would be crucial to not ignore the factor of T/RC here since it stabilizes the filter.

In practice, it may be advantageous to simplify this computation. The idea is to avoid the need for filtering the switch durations. Make the approximation that $\Delta T(k-1)$ equals $\Delta T(k)$ and that 1-T/RC equals 1. Then,

$$\frac{\Delta T(k)}{T} = \frac{LC}{2ET^2}\{v_{REF}[(k+2)T] - (1-2T^2/LC)v_L(kT) - 2T\frac{dv_L}{dt}(kT)\} .$$

The only difference between this equation and the usual one obtained for deadbeat control is that instead of having T in the equations, 2T appears everywhere. This result indicates that the equations are the same as a single bridge. That is, for 192 samples per cycle with two bridges, operate each bridge at 96 samples per cycle with the feedback resistors and capacitors computed as if the sampling rate were 96 times per cycle. The reference is also sent to each bridge at the rate of 96 times per cycle, delayed by 2T, the same delay as at 96 times per cycle.

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