DOE/NASA/0210-1
NASA CR-167950
FCR-4294

Task 4 Completion Report for 40-Kilowatt Grid Connected Modification Contract

(NASA-CR-167950) TASK 4 COMPLETION REPORT FOR 40 KILOWATT GRID CONNECTED MODIFICATION CONTRACT Final Report (United Technologies Corp.) 40 p HC A03/MF A01 CSCL 05A N83-30297 Unclas G3/81 28228

Joseph H. Vogt
United Technologies Corporation
Power Systems Division

June 1983

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
Under Contract DEN 3-210

for
U.S. DEPARTMENT OF ENERGY
Fossil Energy
Office of Coal Utilization and Extraction

and

GAS RESEARCH INSTITUTE

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Office of Coal Utilization and Extraction
Washington, D.C. 20545
Under Interagency Agreement DE-AI21-80ET17088

and

GAS RESEARCH INSTITUTE
Chicago, Illinois 60631

INTRODUCTION

United Technologies Corporation (UTC) designed and developed the 40 kW fuel cell power plant for on-site field test by utilities with United States Department of Energy and Gas Research Institute support. The National Aeronautics and Space Administration has funded the engineering and development to define modifications to a power conditioner and to design and build an add-on package to enable power plant operation either isolated from or connected to the utility grid. The work includes five Tasks:

Task 1:	Conceptual Design
Task 2:	Detailed Design
Task 3:	Procurement, Fabrication and Checkout Testing
Task 4:	Verification Testing
Task 5:	Management Reporting and Documentation

Task 1, Task 2, and Task 3 Completion Reports were submitted and approved. At the completion of Task 4, a Task Completion Report is required and is presented herein. This report also includes the Off Limits Testing results required by "Additional Grid Connect Work" Statement of Work agreement with several utility companies. The brassboard Grid Connect Unit (GCU) was run during the three month period from January to April 1982.

TASK 4 - POWER CONDITIONER VERIFICATION TESTING

The objective of Task 4 is to conduct verification tests designed to demonstrate that the modified power conditioner meets the requirements for grid connected operation.

Subsequent to the Task 2 Completion Report, the following changes have been made to the Grid Connect Unit (GCU) design:

- AC undervoltage/overvoltage protection is now individual line sense and trip -- was average of three line voltages
- Added automatic restart after inverter shutdown when in grid connect mode if shutdown out of limit condition cleared within 4½ seconds
  - Provides capability to have power plant remain running normally or as a minimum at no load net (B1 breaker open)
- Added relay control to retain customer isolated load on utility power after power plant shutdown
  - Upon loss of UPS after shutdown closes SW2 if SW1 is open
- Made various logic software and hardware modifications for stability and noise immunity

A grid connect add-on package and modified brassboard inverter was subjected to the test requirements of FCTS 0556, Verification Test - Development 40 kW Inverter which is attached to this report as Appendix "A". This verification test document defines the test requirements set forth in the approved Verification Test Plan.

Figure 1 shows the test set-up and instrumentation configuration used during verification testing of the GCU. Subsequent to performance of the verification testing described herein, the Grid Connect Utility Advisory Committee met and requested that the AC over/undervoltage protection limit be changed from +10, -7% to +10%, -10%. This change has been reflected in FCTS 0556 as released and was confirmed in the hardware.

The results of the GCU Verification tests are as follows:

Configuration

The brassboard inverter and grid connect add-on package were connected as defined in UTC Drawing FCL-1170 to form the Grid Connect Unit (GCU). A 60 kW, 0 to 200 volt dc laboratory power

Configuration - continued -

supply was connected to the "fuel cell input" terminals of the inverter. A regulated 270 volt, 3 ampere dc supply was connected to start-up power supply connector J1. Laboratory load banks and loads were connected to the inverter output to simulate normal power plant loads and to the customer isolated load terminals TB 106 of the grid connect add-on package to simulate customer loads. A 208 volt, three phase feeder in UTC's South Windsor Facility powered by the Connecticut Light and Power Company was connected to the grid connect add-on package output TB 107 through appropriate disconnect switches and variacs. The test set-up is shown in Figure 1.

Start Up

The start up power supply was set at 270 volts, the inverter start enable switch in the "start" position and B1 breaker left in the open position. Inverter logic power supply and UPS start at about 250 volts from the start up supply, the grid connect add-on logic is energized and contactor SW2 closes connecting the customer isolated loads to the CL&P service through disconnect SW4. All GCU indicating lights are off. When the power supply simulating the fuel cell input was raised. the inverter started at 170 volts dc input and the grid connect add-on package displayed a "ready" light lit, B1 "open", SW1 "open", SW3 "open" and SW2 "closed". This is the correct state for start up of the GCU with the inverter running no-load net, synchronized to its internal crystal and supplying power to the fuel cell power plant ancillary components. The B1 breaker cannot be closed until the inverter is running. After the inverter is running, closing B1 initiates action of the GCU to the selected mode of operation.

Operation in Grid Connect Mode

After start up at no-load net operation as described above and with the mode select switch in the "Grid Connect" position and dispatch power set at 000 (minimum power), the B1 breaker was closed so that the inverter automatically transitioned from crystal synchronization to utility line sync condition. Its output voltage matched to the line voltage and contactor SW1 closed. This put the GCU in grid connect operation with real power flow into the line at a 2 kW minimum power level. The control panel status lights confirmed that B1 breaker was closed, SW1 was closed, SW2 was closed, SW3 was open, and Grid Connect light on. A visicorder trace of this operation is presented in Appendix "B-1".

Shutdown from Grid Connect

The GCU was started and placed in Grid Connect operation at minimum dispatch power. Inverter dc input voltage was reduced and when it reached 128 volts the inverter turned off and GCU lights turn

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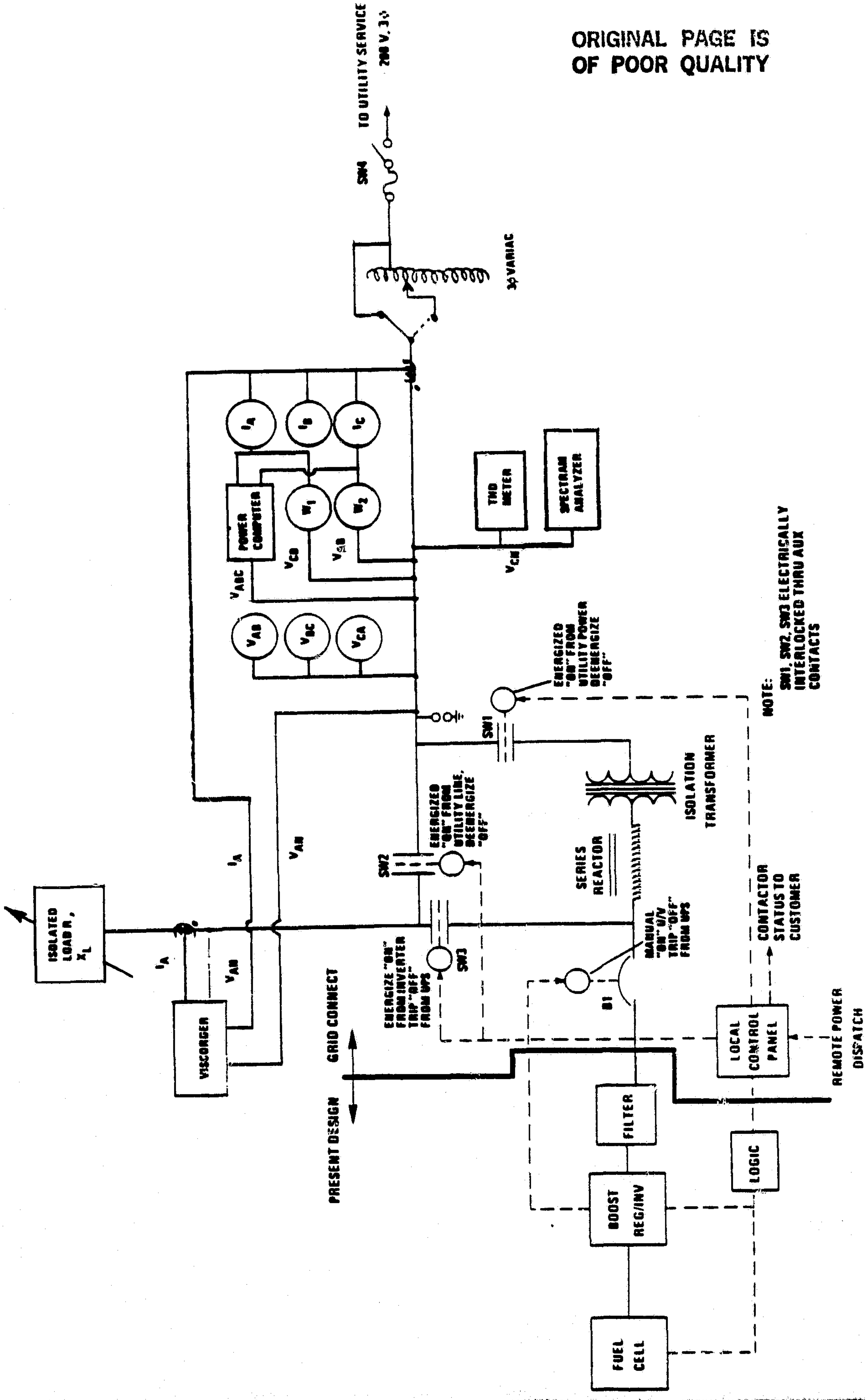


Figure 1. Grid Connect Unit Test and Instrumentation Diagram

Shutdown from Grid Connect - continued -

off. The GCU sequenced through a disconnect with SW1 open, SW3 open, SW2 closed and B1 closed. If the dc input voltage remains low the logic opens B1 breaker after 4½ seconds, several seconds later the UPS shuts down, de-energizing the grid connect add-on package (lights stay off) with the following power switch states: B1 open, SW1 open, SW3 open, and SW2 cycles open and back closed after loss of UPS and remains closed as long as utility service is supplied through SW4.

An additional test was run to define operation if dc voltage recovers after inverter shuts down. When the dc input voltage was returned to 170 volts in less than 4½ seconds the unit sequenced through an inverter restart (GCU lights turn on) and with the utility service within normal voltage limits the unit automatically went into grid connect operation. This sequence was the same for a dispatch level of 40 kW and after returning to grid connect the unit ramped back to the dispatch level in three seconds. Status lights confirmed B1 was closed, SW3 open, SW2 closed, SW1 closed and Grid Connect light on.

Operation in Isolated Mode

The unit was started and put into a ready condition as previously described. In this condition the inverter is running synchronized to its internal crystal at no load net output. With the mode select switch set on Isolated Operation, the B1 breaker was closed resulting in first SW2 opening, then SW3 closing. The unit can now supply up to 47 KVA at .85 PF and satisfy all the isolated load requirements of FCCS 1460, Rev. B. 40 kW Power Plant. Status lights confirmed that SW1 was open, SW2 was open, SW3 was closed, B1 was closed, and Isolated light was on.

Shutdown from Isolated Mode

With the inverter operating in the isolated mode described above, the dc input voltage to the inverter was lowered. When the voltage reached 128 volts, the inverter turned off (GCU lights turn off), B1 breaker opened after 4½ seconds, SW3 opened and SW2 closed. Several seconds later the UPS turned off, all indicator lights stay out and SW2 cycles open and then recloses.

When the dc input voltage to the inverter was returned to 170 volts within 4½ seconds after the inverter turned off, the unit automatically sequenced through an inverter restart and returned to isolated operation. Status lights confirmed B1 was closed, SW1 open, SW2 open, SW3 closed and Isolated light on. Three such cycles within a two minute period, either in isolated or grid connect mode, resulted in the GCU opening the B1 breaker and remaining in an "off" condition with power switch state of B1 open, SW1 open, SW3 open and SW2 closed.

Steady State Operation - Grid Connect, Local Control

The GCU was started and operated in grid connect mode with the local/remote switch set for local control. Dispatch power load was set at min power level, 20 kW and 40 kW with the dc input voltage at 200 volts, 180 volts and 170 volts respectively. Input and output parameter data was taken and efficiency and power factor calculated as follows:

Power Dispatch Pot Setting	E_{Line} Ave Volts	I_{Line} Ave Amps	P_{out} Total kW	V_{dc} Input Volts	I_{dc} Input Amps	η* %	P_f -	THD %
000	208.7	11.6	2.2	201	26.4	38.5	-	1.40
459	208.8	59.9	20.4	180.5	132	84.0	.94	1.55
999	207.8	117.6	40.0	170.0	267	87.4	.95	1.20

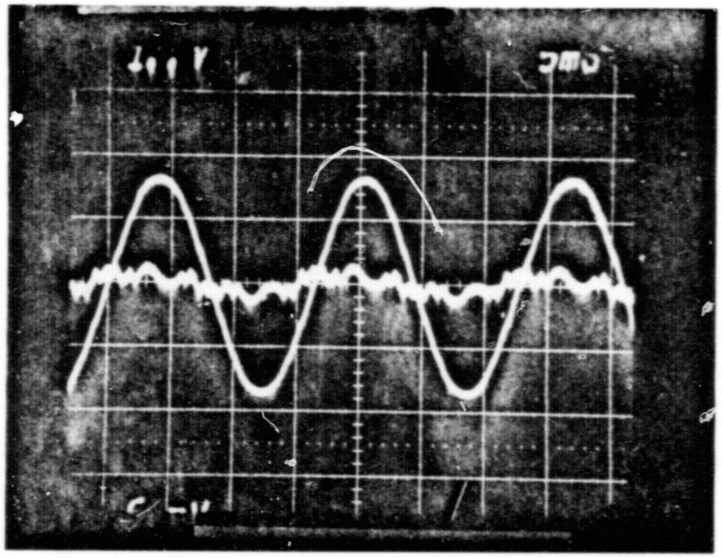
Without the inverter operating, the THD of the line voltage was 0.75%.

Traces of the voltage and current wave form are shown in Figure 2 below.

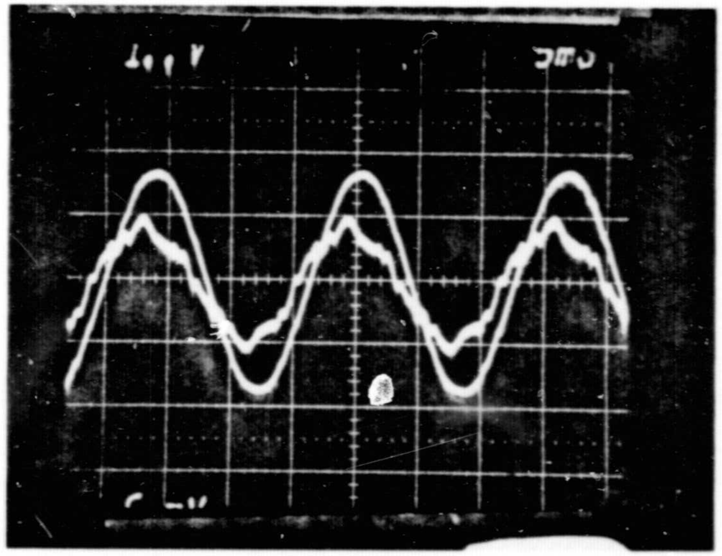
* Efficiency includes an estimated 400 watts ancillary loss (lights, relays, power supply, contactor coils, etc.) in the GCU.

Line voltage harmonic spectrum data while in grid connect at dispatch power loads of 2, 20 and 40 kW is as follows:

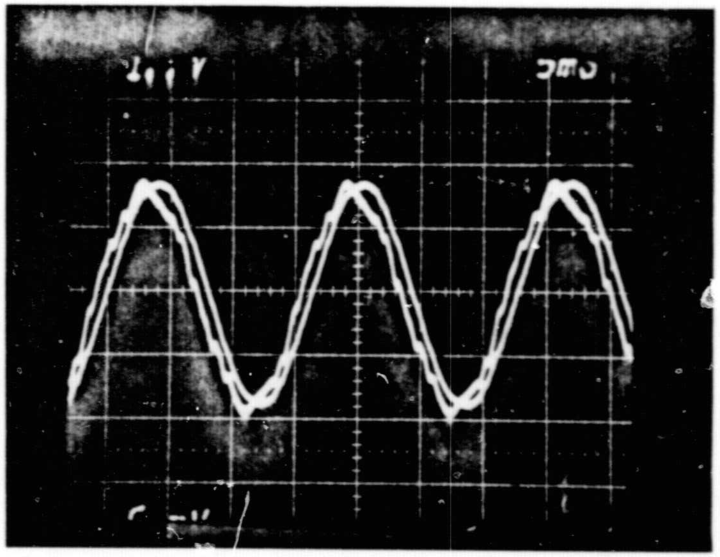
Dispatch Pot Setting	P_{out} kW	Harmonic 5th	7th	11th	13th	17th	19th
		dB Down From Fundamental					
000	2.2	41.3	48.5	55.2	55.4	47.5	50.4
459	20.4	38.6	47.7	48.5	53.0	48.7	51.7
999	40.0	41.2	53.2	49.6	54.7	50.6	50.7



DISPATCH POWER 2.2 kW



DISPATCH POWER 20 kW



DISPATCH POWER 40 kW

FIGURE 2. CURRENT AND VOLTAGE SCOPE TRACES

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Steady-State Operation - Grid Connect, Remote Dispatch

The GCU was operated with "remote" switch "on" dispatched remotely. Results of this test were the same as presented above. Minimum power was at 4 ma and 40 kW was at 20 ma remote signal.

Transfer from Grid Connect to Isolated Mode

With the GCU operating in grid connect, the mode select switch was moved from the Grid Connect position to the Isolated position. Contactor SW1 immediately opened, the inverter logic transitioned from utility line sync to internal crystal sync, and voltage regulation SW2 opened and SW3 closed. The unit ran isolated powering an external load from several to 40 kW through SW3. Status lights confirmed B1 closed, SW1 open, SW2 open, SW3 closed, and Isolated light on. This type of transfer was performed at dispatch loads from minimum power of 2 kW to 40 kW. Transfer from Grid Connect to Isolated Mode can only be done by manual activation of the mode select switch at the local control panel, or automatic operation of the GCU sequencing logic for utility line out of limit conditions for greater than 30 seconds.

Transfer from Isolated to Grid Connect Mode

With the GCU operating in the isolated mode, the mode selector switch was moved from the Isolated position to the Grid Connect position.* Contactor SW3 opened, SW2 closed and the inverter logic transitioned from internal crystal sync to line sync and adjusted inverter voltage to line match. Contactor SW1 closed and the GCU ramped to the dispatch level which was set at minimum power, 20 kW and 40 kW for the various runs. Each time the status lights verified B1 closed, SW3 open, SW2 closed, SW1 closed and the Grid Connect light was on. Transfer from Isolated to Grid Connect can only be done locally. A visicorder trace of this mode change is presented in Appendix "B-2".

Note: If the unit had automatically switched to isolated previously, then in order to return to grid connect the mode select switch must be reset to isolated and back to grid connect.

Steady-State Low AC Voltage Disconnect (Three Phase)

With the GCU operating in grid connect at 40 kW dispatch load, the "utility line" voltage was lowered to 193 Vac line-to-line by means of a three phase variac. At the 193 volt level, the inverter turned off and the GCU disconnected. SW1 opened and four and one half seconds later the inverter restarted with logic on crystal sync and regulated output voltage. After thirty seconds the GCU went to isolated by opening SW2 and closing SW3. The status lights confirmed B1 closed, SW1 open, SW2 open, SW3 closed and the Isolated light was on.

Steady-State Low AC Voltage Disconnect (Three Phase) - continued -

In order to simulate a temporary line loss, this test was repeated through the step where the GCU disconnected from the utility line. The voltage was then immediately raised to 199 volts (197 is -5%). After four and one half seconds, the inverter restarted, and two seconds later the inverter logic resynchronized to the line and adjusted the output voltage to line match, then closed SW1 and ramped to dispatch load level. The status lights confirmed B1 closed, SW3 open, SW2 closed, SW1 closed, and Grid Connect light on. Visicorder traces of low AC disconnect and return to grid connect, and low AC disconnect and return to isolated mode are presented in Appendix "B-3" and "B-4".

When the unit was repeatedly cycled through low AC disconnect and back to grid connect, on the third disconnect from the utility within two minutes, the GCU automatically cycled to the isolated mode with B1 closed, SW1 and SW2 open, and SW3 closed. Subsequent to the above testing, the operating limits were changed to ±10% by the Grid Connect Committee. The low voltage disconnect therefore will occur at approximately 187 volts. This change was made and verified.

Transient Low AC Voltage Disconnect

The GCU was configured with a three pole, manual transfer switch and a three phase Y connected variac to provide for connection either to the line directly or to the line through the variac at reduced voltage. Actuation of this switch caused the GCU to sense a "loss of 3Ø AC line" and operate as described below for Disconnect on Loss of AC Line. The switch could not be actuated fast enough to simulate a transient low ac line and actuate the pole overcurrent protection. However, once during normal GCU operation in the grid connect mode the Connecticut Light and Power line did go through a major excursion due to a fault or reclosure action and the GCU cycled automatically through a disconnect mode back to grid connect, which confirmed the pole overcurrent protection.

High AC Voltage Disconnect

The "utility line" voltage was raised to 229 volts and the inverter turned off and SW1 opened. The inverter then restarted in four seconds with its logic synchronized to an internal crystal and regulated the output voltage. After 30 seconds the GCU went to Isolated operation by opening SW2 and closing SW3. The status lights confirmed B1 closed, SW1 open, SW2 open, SW3 closed and Isolated light on. The overvoltage test while in grid connect was repeated through the disconnect state with SW1 open, at which time line voltage was returned to 218 volts and the inverter logic automatically re-synchronized with the line, adjusted the output voltage to a line match condition, the GCU sequenced to grid connect and ramped to dispatch load level. Status lights confirmed B1 closed, SW3 open, SW2 closed, SW1 closed and Grid Connect light on.

AC Line Voltage Unbalance Disconnect (Single Phase)

Three single phase variacs were connected to allow individual reduction of each phase voltage sense circuit of the GCU. The sensed voltages were set at 120 volts per phase and the GCU was placed in Grid Connect operation at minimum power dispatch. Phase A sense variac was adjusted to reduce the GCU sensed voltage and at 112 volts the inverter turned off, SW1 opened and four and one half seconds later the inverter restarted and ran synchronized to an internal crystal and with regulated output voltage. After 30 seconds of sensed low ac voltage, the GCU sequenced to isolated operation by opening SW2 and closing SW3. The status lights confirmed that B1 was closed, SW1 open, SW2 open, SW3 closed, and the Isolated light was on.

Disconnect on Loss of AC Line (Three Phase)

The GCU was operated in grid connect at 40 kW dispatched power level and 47 KVA isolated load connected. Test disconnect SW4 was opened simulating complete loss of line and utility system load. The inverter turned off and the GCU disconnected by opening SW1. Four and one half seconds later the inverter restarted with its logic synchronized to its internal crystal and with output voltage regulated. Thirty seconds later the GCU went to isolated by opening SW2 and closing SW3. Status lights confirmed that B1 was closed, SW1 open, SW2 open, SW3 closed, and the Isolated light was on.

This test was repeated for (1) 40 kW dispatch load, zero isolated load connected and 6.5 KVA simulating minimum power plant ancillary loading, (2) 40 kW dispatch load and a 10 HP, 3Ø motor running, (3) minimum dispatch power and a 10 HP, 3Ø motor, and (4) dispatch load equal to the isolated load of 23 KVA plus a 10 HP, 3Ø motor, 1½ HP, 3Ø motor and a ½ HP 1Ø motor. A visicorder trace of this latter case is presented in Appendix "B-5". In all cases the GCU disconnected itself from the utility line and returned automatically to the line when the line was reconnected within a 25 second period and remained within limits for 5 seconds. When the disconnect was left open the GCU went to isolated mode of operation. Below 6 KVA the GCU continued to run and did not go through a "disconnect" operation, however, this is not a possible power plant ancillary load condition since actual load under these conditions is higher and cycling.

Loss of One Phase (Short)

A 100 ampere, 400 volt semiconductor, current limiting fuse was inserted in series with phase "A" line on the GCU side of switch SW4 shown in Figure 1. A single pole, single throw "shorting" switch was connected on the inverter side of this 100 amp fuse to neutral (ground). The GCU was operating in the grid connect mode at a 40 kW dispatch level and an isolated load of 47 KVA and this shorting switch was actuated to the closed position and immediately opened. The inverter turned off instantaneously and SW1 opened. Four and one half seconds later the inverter restarted and ran on its internal clock with B1 closed, SW2 closed, and SW3 and SW1 open for 30 seconds and then automatically went to isolated mode with SW3 closed. The 100 amp semiconductor fuse was open.

Loss of One Phase (Short) - continued -

The fuse was replaced and the test repeated at minimum power dispatch level and zero isolated load with the same results, except the unit ran at no-load isolated.

Both the fuse holder and the shorting switch were moved to phase "B" and both of the above tests repeated with the same results.

Loss of One Phase (Open)

A single pole, single throw disconnect switch was connected in series with phase "A" on the GCU side of switch SW4. The GCU was operated in grid connect mode at 20 kW dispatch load and an isolated load of 23 KVA. The single pole disconnect was opened and left open. The GCU continued to operate into the line supplying current into phases B and C and was unable to detect the loss of phase "A". The test was repeated for phase "C" with the same results. Failure to detect loss of a single line (phase) in utility systems is not unusual. However, when the test was repeated with the disconnect in phase "B", the GCU went to no load net condition with B1, SW1 and SW3 open and SW2 closed. This latter test was repeated several times with the same results. The cause of this resulting action is not known, however, it is the preferred action under these conditions.

Loss of Line with Motor Load

A 10 HP, 3Ø motor, 1½ HP, 3Ø motor, and a ½ HP 1Ø motor were connected to the isolated load bus of the GCU. The GCU was operated in Grid Connect at a dispatch load of 40 kW and an isolated load of 23 KVA with motors running. Disconnect SW4 was opened and the inverter shutdown and SW1 opened. After 4½ seconds the inverter restarted and ran for 30 seconds synchronized to its internal clock with B1 and SW2 closed and Sw1 and SW3 open. At this time SW2 opened and SW3 closed putting the unit into isolated operating mode and the motors restarted and ran. This test was repeated for 20 kW dispatch with the same results.

The GCU was then run in Grid Connect mode with the dispatch load set equal to an isolated load of 23 KVA, including the above described motors running. Disconnect SW4 was then opened and reclosed causing the inverter to turn off and SW1 to open. After four and one half seconds the inverter restarted and several seconds later the GCU returned to Grid Connect with B1, SW2 and SW1 closed and SW3 open. A visicorder trace of this sequence is presented in Appendix "B".

Over and Under Frequency

The Power Systems Division's 100 KVA laboratory test alternator was not available at the GCU test setup and would have required

Over and Under Frequency - continued -

considerable facility changes to make it compatible for this test. Instead, the unit was operated at no-load net with an adjustable oscillator connected to the logic in place of the bill-of-material crystal. The oscillator was increased and decreased in frequency (simulating abnormal line frequency) and the inverter protection circuitry turned the inverter off at 57.1 Hertz and 63.0 Hertz. These values are the same as set for isolated operation and are not adjustable in the present 40 kW inverter design.

Steady State and Transient Operation (Isolated)

The GCU was operated in the isolated mode condition. Checks were made in both steady state and transient load conditions. Its performance did not differ from tests made prior to changing the logic configuration from strictly a stand-alone unit to the current GCU configuration. Complete operating data matrix was not taken, but the following is a summary of the checks.

- Output voltage regulation was within 120 volts ± 5% from no load to peak power
- At full load the THD was 7%
- Efficiency was about 91% at full load
- Started 10 HP, 3Ø motor at 30 kW preload
- Survived both line to line and line to neutral faults

APPENDIX "A"

FCTS 0556

VERIFICATION TEST - DEVELOPMENT,

40 kW GRID CONNECT INVERTER

FCTS 0556

FUEL CELL

TEST SPECIFICATION

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VENDOR CODE IDENT.	PART OR IDENTIFYING NO.	REV LTR	NOMENCLATURE OR DESCRIPTION

UNITED TECHNOLOGIES POWER SYSTEMS

TITLE

VERIFICATION TEST - DEVELOPMENT,
40 kW GRID CONNECT INVERTER

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REV

PAGE 1 OF 13

FCO FORM No. 0205A Rev. 10/13/81

1.0 SCOPE •

This specification establishes the test requirements and criteria for the development verification tests of the PC 18B 40 kW inverter in grid connect operation.

1.1 Description

The 40 kW inverter consists of a boost regulator stage, inverter stage, input and output filter, logic and "Scott-T" autotransformer. In isolated operation the inverter takes dc fuel cell power and converts it to regulated, three-phase, 4-wire ac power with a current limited characteristic for over-loads up to bolted faults. In grid connect operation this same inverter plus an add-on grid connect package operates in parallel with the utility service to give up to 40 kW of dispatched power to the utility line. The add-on grid connect package consists of a series reactor and output isolation transformer, logic for grid synchronization and protection, and switches for connecting and disconnecting the inverter in the desired operating modes.

2.0 APPLICABLE DOCUMENTS

2.1 PC 18 B-3 Diagram, Installation, XFC 4552

2.2 40 kW Inverter Electrical Diagram, FC 4398

2.3 40 kW Grid Connect Electrical Diagram, FCL 1170

3.0 REQUIREMENTS

3.1 Verification Test

A verification test to demonstrate conformance to the following performance requirements shall be conducted on the Brassboard inverter and Grid Connect development unit as described in 3.1.2. A definition of parameters is given in 3.2.

3.1.1 Verification Requirements

3.1.1 Power Output

In grid connect operation the inverter shall deliver from ~2 to 40 kW at .95 lead to .95 lag power factor into the utility line at a line voltage of 208 V + 10%, - 10%.

3.1.1.2 Voltage

In grid connect operation the nominal ac output voltage from the isolation transformer is 3-wire, 208 volts rms line-to-line. Nominal ac output voltage in isolated operation is 120 volts rms line-to-neutral and 208 volts rms line-to-line 4-wire.

3.1.1.3 Efficiency

3.1.1.3.1 In grid connect operation the inverter and add-on package efficiency at 40 kW shall be ≥ 86.4% with 170 volts dc input.

3.1.1.3.2 In isolated operation the steady state efficiency with 187 volts dc input shall be ≥ 86.2% at 20 kW ac three-phase net output at 0.85 power factor plus 1.825 kW ac three-phase parasite power and 375 VA single phase UPS power. All three-phase loads will be balanced.

3.1.1.3.3 In isolated operation the steady state efficiency with 160 volts dc input shall be ≥ 89.5% at 40 kW ac three-phase net output at 0.85 power factor plus the other loads given in Section 3.1.1.3.2.

3.1.1.4 Peak Power

The transient gross peak power shall be 57.4 kW ac at 0.7 power factor for 5 seconds in isolated operation.

3.1.1.5 Voltage Regulation

In grid connect operation the inverter follows the utility line voltage over a range of 208 volts + 10% and - 10% and delivers power as defined in 3.1.1. The voltage regulation from no load to peak power shall be ± 5% in isolated operation.

In grid connect operation the inverter shall attain within 5% of the dispatched power setting within 2 seconds for power changes up to 40 kW. For transients between no load and rated power in isolated operation the output voltage shall recover to within 5% of final steady state within 2 cycles for both up and down transients.

3.1.1.6 Light Flicker

There shall be no discernible light flicker for application and removal of a 20% of rated load step above 20% rated power in isolated operation. Not applicable for grid connect operation.

3.1.1.7 **Input Current Ripple**

The maximum ripple current at inverter input shall be 25 amperes rms at rated power.

3.1.1.8 **Frequency**

The frequency of the inverter is synchronized to utility frequency in grid connect operation and can operate at line frequencies within the range of 57 Hz to 63 Hz. The accuracy of the inverter output frequency shall be .0002% in isolated operation.

3.1.1.9 **Fault Current - Isolated Operation Only**

The line-to-line three-phase bolted fault current shall be capable of 250 amperes maximum for 5 seconds ± 2 seconds for isolated operation. The line-to-line line-neutral bolted fault current shall be capable of 400 amperes maximum for 5 seconds ± 2 seconds.

3.1.1.10 **Total Harmonic Distortion** (THD)

The THD for isolated operation shall be ≤8%, with any single harmonic less than 5% at 100% rated load.

* When in Grid Connect with a line impedance of .0216 ohms/phase (5% X_L, 100 KVA transformer) the voltage THD will be ≤4% and single frequency harmonics will be ≤2%.

3.1.2 **Verification Test Requirement**

3.1.2.1 **Start Up**

A regulated 270 volt, 3 a, dc power supply shall be connected to the inverter start up power supply connector and a 0-200 volts dc variable voltage power supply to the fuel cell input connector. In the grid connect configuration (Reference Figure 1) and with system switches in the start up mode (SW1 open, SW2 open, B1 open and toggle switch set for local control) the inverter shall be started by applying an "Inverter Start Enable" signal to the inverter logic and increasing input dc voltage. The inverter shall start at about 170 to 180 volts dc and run at no load on internal synch, and display a "Ready" signal at the Local Control Panel.

3.1.2.2 **Operation in Grid Connect Mode**

Following start up per 3.1.2.1 when the mode selector switch is actuated to the Grid Connect position and B1 breaker is closed on the local panel, the inverter logic will synch the frequency to the utility line, adjust inverter output voltage phase and magnitude to match the utility line and close SW1. With the dispatched power at zero setting, verify switch status

* For reference only

3.1.2.2 Operation in Grid Connect Mode - continued -

(B1 closed, SW1 closed, SW2 closed, SW3 open) and delivery of minimum power of about 2 kW.

3.1.2.3 Shutdown from Grid Connect Mode

When dc voltage input to the inverter is reduced, the inverter will shut down when input voltage drops to 120 $\pm^{10}_{0}$ volts VDC and switch B1 will open. Verify status of switches (B1 open, SW1 open, SW2 closed, SW3 open). The customer load should now be supplied by the utility line through SW2.

3.1.2.4 Operation in Isolated Mode

Start the inverter per 3.1.2.1. Switch the mode selector switch to Isolated mode and close the output breaker B1. Verify status of switches (B1 closed, SW1 open, SW2 open, SW3 closed) and the inverter supplying customer full load of 40 kW at .8 pf.

3.1.2.5 Shutdown from Isolated Mode

Following operation in Isolated mode per 3.1.2.4, repeat requirements in 3.1.2.3, including verification of switch status.

3.1.2.6 Steady-State Operation - Grid Connect, Local Control

Start the inverter per 3.1.2.1 and 3.1.2.2 and confirm operation in grid connect mode. With dispatch 0, 20 and 40 kW gross power output into the utility line at 200, 180 and 170 volts dc respectively, and record and calculate the following:

a) All output line-to-line voltages, ac volts rms.
b) All output line currents.
c) Phase A, B, and C output power, ac watts.

) At the utility interface with the grid connect add-on package

d) DC voltage (volts) and current (amperes) average input to the inverter.

e) Calculate efficiency (η), KVA and power factor. The inverter must meet or exceed the efficiency stated in 3.1.1.3.1.

f) Output voltage THD as a percentage of voltage using THD meter and harmonic voltage spectrum of line voltage using spectrum analyzer.

3.1.2.6 Steady-State Operation - Grid Connect, Local Control

f) - continued -

1. Without inverter operating
2. With inverter operating (in grid connect mode).

g) Recorded traces of voltage and current waveforms.

3.1.2.7 Steady-State Operation - Grid Connect, Remote Dispatch

With the toggle switch for Remote Dispatch, start the inverter per 3.1.2.1 and 3.1.2.2. Verify status of switches (B1 closed, SW1 closed, SW2 closed, SW3 open). Verify remote dispatched power from 0 to 40 kW and record data per 3.1.2.6 (a), (b), (c), (d), and (e).

3.1.2.8 Transfer from Grid Connect to Isolated Mode

With the toggle set at local control, start inverter per 3.1.2.1 and 3.1.2.2. Transfer operation to Isolated Mode and verify the inverter disconnected from the utility line by opening SW1, transferred to operation on internal crystal synch and is powering the customer's load in isolated operation through B1 and SW3. Verify status of switches for Isolated operation (B1 closed, SW1 open, SW2 open, SW3 closed).

3.1.2.9 Transfer from Isolated to Grid Connect Mode

While operating as in 3.1.2.8 and with the dispatch power setting at zero, 50% power and 100% power, switch the mode selector switch to the Grid Connect position at the Local Control Panel. The inverter shall synch to the frequency of the line, adjust inverter output voltage phase and magnitude to match the utility line and control switches to transfer to grid connect operation and ramp to dispatch level. Verify status of switch for grid connect operation (B1 closed, SW1 closed, SW2 closed, SW3 open) and power output.

3.1.2.10 Grid Connect Off-Limit Operation

With the inverter operating in the Grid Connect mode perform the following off-limit tests.

3.1.2.10.1 Steady-State Low AC Voltage Disconnect

Through a variac, gradually reduce the effective line voltage. Record the voltage that causes grid disconnect due to low ac voltage. This shall be 187 ± 2 volts ac.

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3.1.2.10.1 Steady-State Low AC Voltage Disconnect - continued -

Verify switch status indicating that the inverter has gone to isolated operation (B1 closed, SW1 open, SW2 open, SW3 closed).

3.1.2.10.2 Transient Low AC Voltage Disconnect

Configure the system to change the inverter output voltage instantaneously from 208 Vac to under 193 Vac, and bring it back to 208 Vac in less than two seconds. With the inverter operating at rated load in the Grid Connect mode and rated isolated load converted, reduce the inverter output voltage to 193 Vac for less than two seconds. Continue reducing the voltage level until the inverter disconnects. Verify that switch status indicated that the inverter went to disconnect operation (B1 closed, SW1 open, SW2 closed, SW3 open) and then returned automatically to grid controlled operation (B1 closed, SW1 closed, SW2 closed, SW3 open) and ramped back up to rated load dispatched to the utility line.

3.1.2.10.3 AC Line Voltage Unbalance Disconnect

Repeat 3.1.2.10.1, except reduce the voltage in only one phase at a time. With the inverter operating at rated load in the Grid Connect mode, reduce the inverter output voltage successively on phases A, B, and C, recording each phase voltage causing grid disconnect. Verify for each phase that the switch status indicates that the inverter has gone to isolated operation (B1 closed, SW1 open, SW2 open, SW3 closed).

3.1.2.10.4 Disconnect on Loss of AC Line

With the inverter operating in the Grid Connect mode at rated dispatched power level and rated isolated load, open the three-phase line disconnect SW4 to give loss of ac line. Verify switch status indicated that inverter has gone to isolated operation (B1 closed, SW1 open, SW2 open, SW3 closed). Repeat for zero isolated load.

3.1.2.10.5 Loss of One Phase (Short)

With the inverter connected with a shorting switch from Phase B to neutral on the inverter side of fused disconnect switch SW4, and the inverter operating in grid connect mode at dispatch rated 40 kW output and a customer system load of 47 KVA activate the shorting switch and verify that the system goes to isolated operation with B1 closed, SW1 open, SW2 open and SW3 closed. Repeat this test for zero kW dispatch load level and also for customer system load of zero KVA.

3.1.2.10.6 Loss of One Phase (Open)

With the inverter connected with single pole disconnect switches in Phase A and Phase B on the inverter side of disconnect switch SW4 and the inverter operating in grid connect mode at dispatch load of 20 kW and a customer system load of 23 KVA, open Phase A switch only and record system operation. Repeat test and open Phase B switch only. Repeat both tests with dispatch load of 40 kW.

3.1.2.10.7 Loss of Line with Motor Load

With the inverter connected for grid connect operation, open the disconnect SW4 switch for all six combinations of the following load conditions and verify that the system has gone to isolated load with switch status of B1 closed, SW1 open, SW2 open and SW3 closed.

Dispatch loads - Zero power, 20 kW (half power) and 40 kW (full power).

Customer System Load - 47 KVA and 23 KVA (including 10 HP 3Ø Motor. 1 HP 3Ø motor and 1/2 HP 1Ø motor).

3.1.2.10.8 Over and Under Frequency

With the inverter connected with output of SW4 connected to a variable frequency 100 KVA laboratory test alternator instead of the utility line, vary the alternator frequency up and down and record the frequency that the inverter disconnects from the line and goes to isolated operation. Verify switch status of B1 closed, SW1 open, SW2 open and SW3 closed. Perform this test for customer connected load of 47 KVA and an external load on alternator of 40 KVA and at dispatch power of 20 kW and 40 kW.

3.1.2.11 Steady-State Operation - Isolated Mode

Operate the inverter in the Isolated mode with balanced loads, and record and calculate the following at 0% (tare) 50% and 100% of rated gross power output at 200, 180, and 170 volts dc input respectively.

a) All output line-to-line and line-to-neutral voltages, ac volts rms.

b) All output line currents, ac amperes rms.

c) Phase A, B, and C output power, ac watts.

d) DC voltage (volts) and current (amperes) average input to the inverter.

3.1.2.11 Steady-State Operation - Isolated Mode - continued -

e) Calculate efficiency (η), KVA and power factor. The inverter must meet or exceed the efficiencies stated in 3.1.1.3.

f) Output voltage THD and harmonic voltage spectrum as a percentage of fundamental. Values shall be as stated in 3.1.1.10.

g) Recorder traces of voltage and current wave forms.

3.1.2.12 Transient Response

Perform transient load testing with both up and down transients with balanced loads at an input voltage of 210 volts dc. Take recorder traces of line-to-neutral voltages and line currents and record subjective observation of light flicker for the following transient balanced loads:

a) 20% step loads from 20%, 50% and 80% of rated load.

b) 50% rated power to peak power.

c) Rated power to peak power.

d) 10 H.P. motor starting. The inverter shall meet the requirements of 3.1.1.5 and 3.1.1.6.

3.2 Definitions

The following definitions apply in making inverter performance calculations.

a) Average line current (I_{ave})

$$I_{ave} = 1/3 \times (\Sigma \text{ individual rms line currents}), \text{ amperes}$$

b) Average line-to-neutral voltage (V_{ave})

$$V_{ave} = 1/3 \times (\Sigma \text{ individual rms line-to-netral voltages}), \text{ volts}$$

c) Apparent Power (kVA)

$$kVA = 3 \times I_{ave} \times V_{ave} \div 1000, \text{ kilovolt amperes}$$

d) Power per phase ($P\emptyset$)

$$P\emptyset = V\emptyset \times I\emptyset \times \cos\theta\ (V-I) \div 1000, \text{ kilowatts}$$

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3.2 Definitions - continued -

e) Output power (P_T)

$$P_T = (P\varnothing A + P\varnothing B + P\varnothing C) \div 1000, \text{ kilowatts}$$

f) Power factor (pf)

$$pf = P_T \div kVA \text{ (dimensionless)}$$

g) Percent efficiency (η)

$$\eta = (P_T \times 100) \div P_{dc}, \%$$

h) Load unbalance

$$I_{max} - I_{min}$$

3.3 Verification Criteria Definition

3.3.1 Rejection

If the GCU fails to meet the verification test requirements, the design shall be subjected to Engineering Review and action.

3.3.2 Retest

If the GCU fails the verification criteria due to a correctable cause, the inverter shall be retested. Retesting need include only those tests not successfully completed and those tests necessary to check the results of any corrective action.

4.0 QUALITY ASSURANCE PROVISIONS

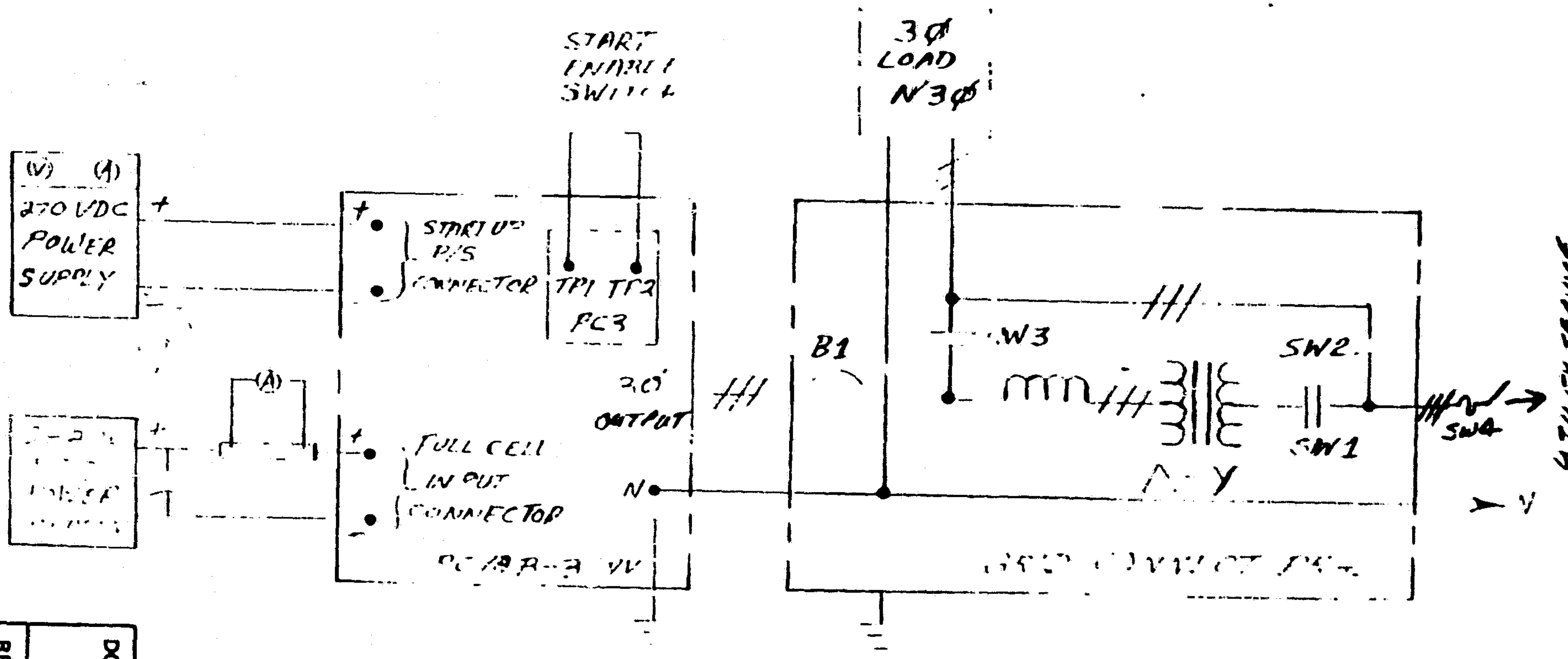
4.1 QA shall audit this test to insure compliance with the requirements.

4.2 QA shall indicate approval in the space provided on the 40 kW Grid Connect Inverter Verification Sheet (Page 12).

40 kW GRID CONNECT INVERTER VERIFICATION

		Engineer	Date
3.1.2.1	Start-Up		
3.1.2.2	Operation in Grid Connect Mode		
3.1.2.3	Shutdown from Grid Connect Mode		
3.1.2.4	Operation in Isolated Mode		
3.1.2.5	Shutdown from Isolated Mode		
3.1.2.6	Steady-State Operation - Grid Connect, Local Control		
3.1.2.7	Steady-State Operation - Grid Connect, Remote Dispatch		
3.1.2.8	Transfer from Grid Connect to Isolated Mode		
3.1.2.9	Transfer from Isolated to Grid Connect Mode		
3.1.2.10.1	Steady-State Low AC Voltage Disconnect		
3.1.2.10.2	Transient Low AC Voltage Disconnect		
3.1.2.10.3	AC Line Voltage Unbalance Disconnect		
3.1.2.10.4	Disconnect on Loss of AC Line		
3.1.2.10.5	Loss of One Phase (Short)		
3.1.2.10.6	Loss of One Phase (Open)		
3.1.2.10.7	Loss of Line with Motor Load		
3.1.2.10.8	Over and Under Frequency		
3.1.2.11	Steady-State Operation Isolated Mode		
3.1.2.12	Transient Response		

Quality Assurance ______________________________



NOTE: CONNECTIONS TO BE MADE USING FOLLOWING REFERENCES;

XFC 4552, PC18B-3 DIAGRAM INSTALLATION

FC 4398, 40KW INVERTER ELECTRICAL DIAGRAM

FCL 1170, 40KW GRID CONNECT ELECTRICAL DIAGRAM.

FIG. 1 ONE LINE DIAGRAM – GRID CONNECT TESTS

DOCMT. NO.	
FCTS 0556	
REVISION	PAGE 13

APPENDIX B-1

VISICORDER TRACE - TRANSITION FROM READY STATE TO GRID CONNECT MODE AT 40 kW DISPATCH LEVEL.

(1) GCU IS AT READY WITH INVERTER RUNNING AT NO LOAD NET, B-1, SW-1 AND SW-3 OPEN, SW-2 CLOSED, WITH LINE FEEDING 18 kW ISOLATED LOAD.

B-1 BREAKER IS MANUALLY CLOSED AND INVERTER SYNCHRONIZES WITH LINE WITHIN 2 SECONDS AND ENERGIZES GCU ISOLATION TRANSFORMER.

(2) SWITCH SW-1 CLOSES.

(3) GCU RAMPS UP TO DISPATCH LOAD SETTING OF 40 kW WITHIN ONE SECOND.

(4) GCU OPERATES STEADY STATE AT DISPATCH LOAD SETTING WITH 18 kW SUPPLIED TO ISOLATED LOAD AND 22 kW SUPPLIED TO UTILITY LINE.

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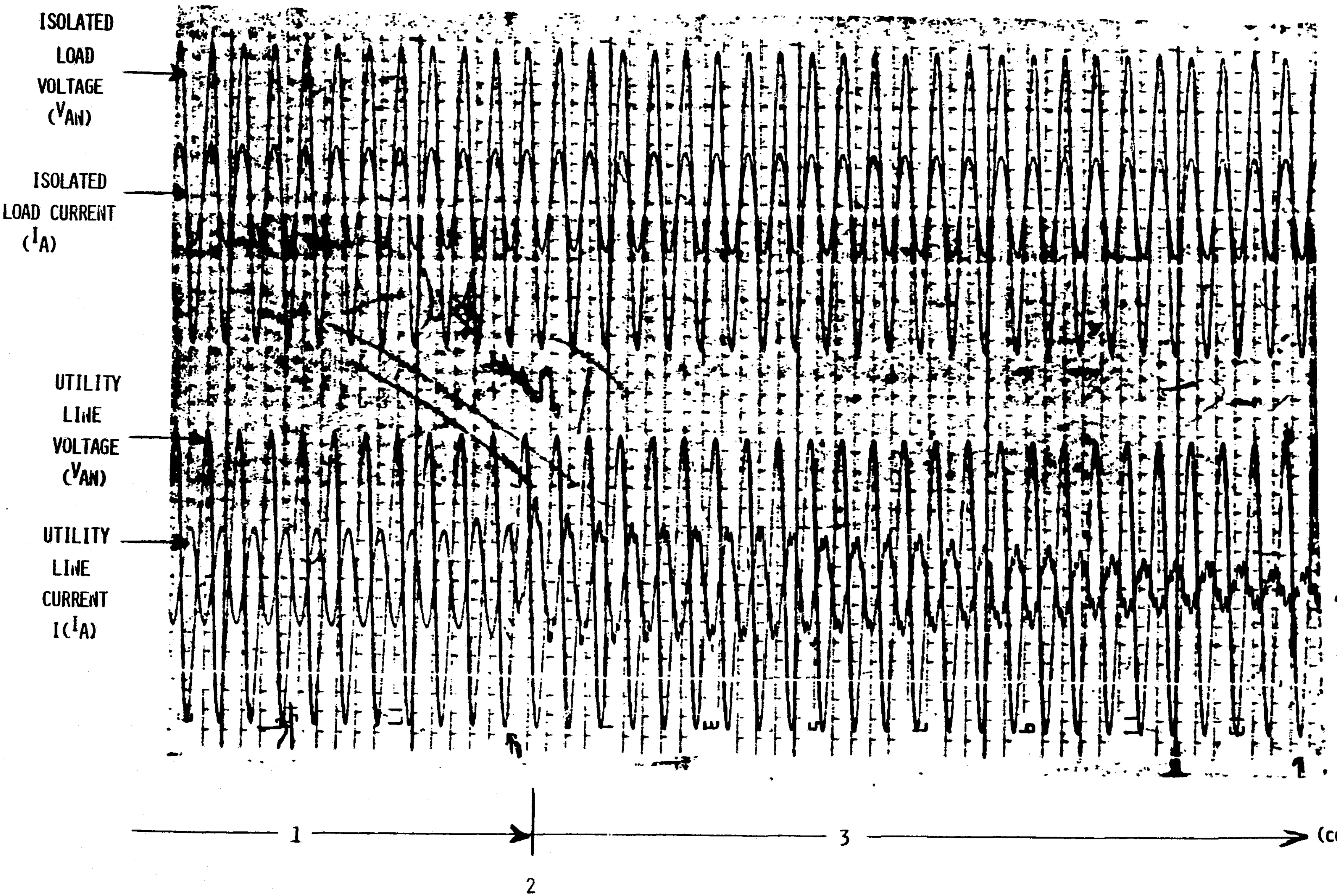
APPENDIX B-1 VISICORDER TRACE - "READY" STATE TO GRID CONNECT MODE



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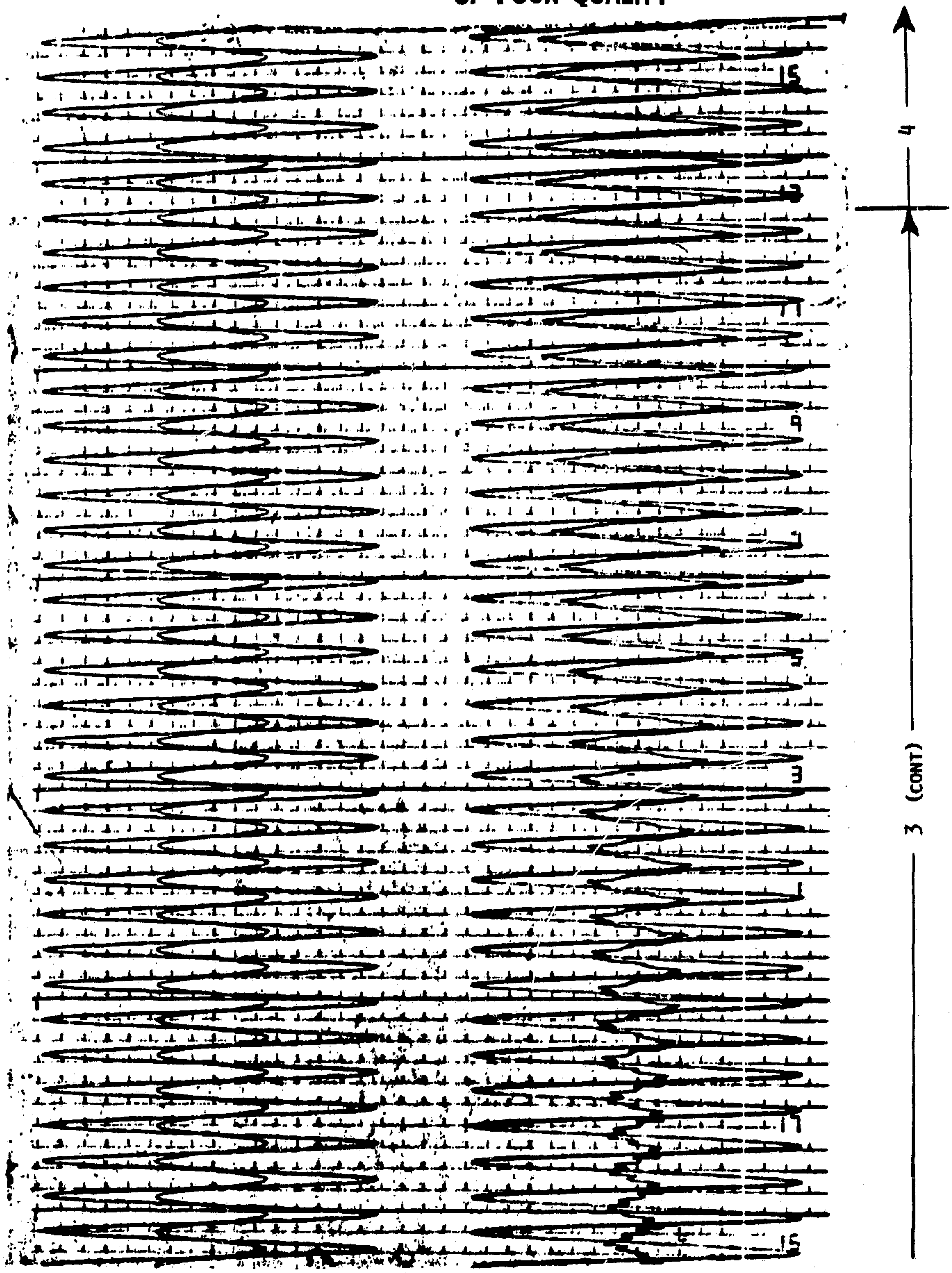


APPENDIX B-1 VISICORDER TRACE - "READY" STATE TO GRID CONNECT MODE (CONT)

APPENDIX B-2

VISICORDER TRACE - TRANSFER FROM ISOLATED MODE TO GRID CONNECT MODE:

(1) GCU OPERATING IN ISOLATED MODE AT 18 kW LOAD. B-1 AND SW-3 CLOSED, SW-1 AND SW-2 OPEN.

(2) MODE SELECT CHANGED FROM ISOLATED TO GRID CONNECT MODE AND SW-3 OPENS.

(3) SW-2 CLOSES 6/10 SECONDS LATER.

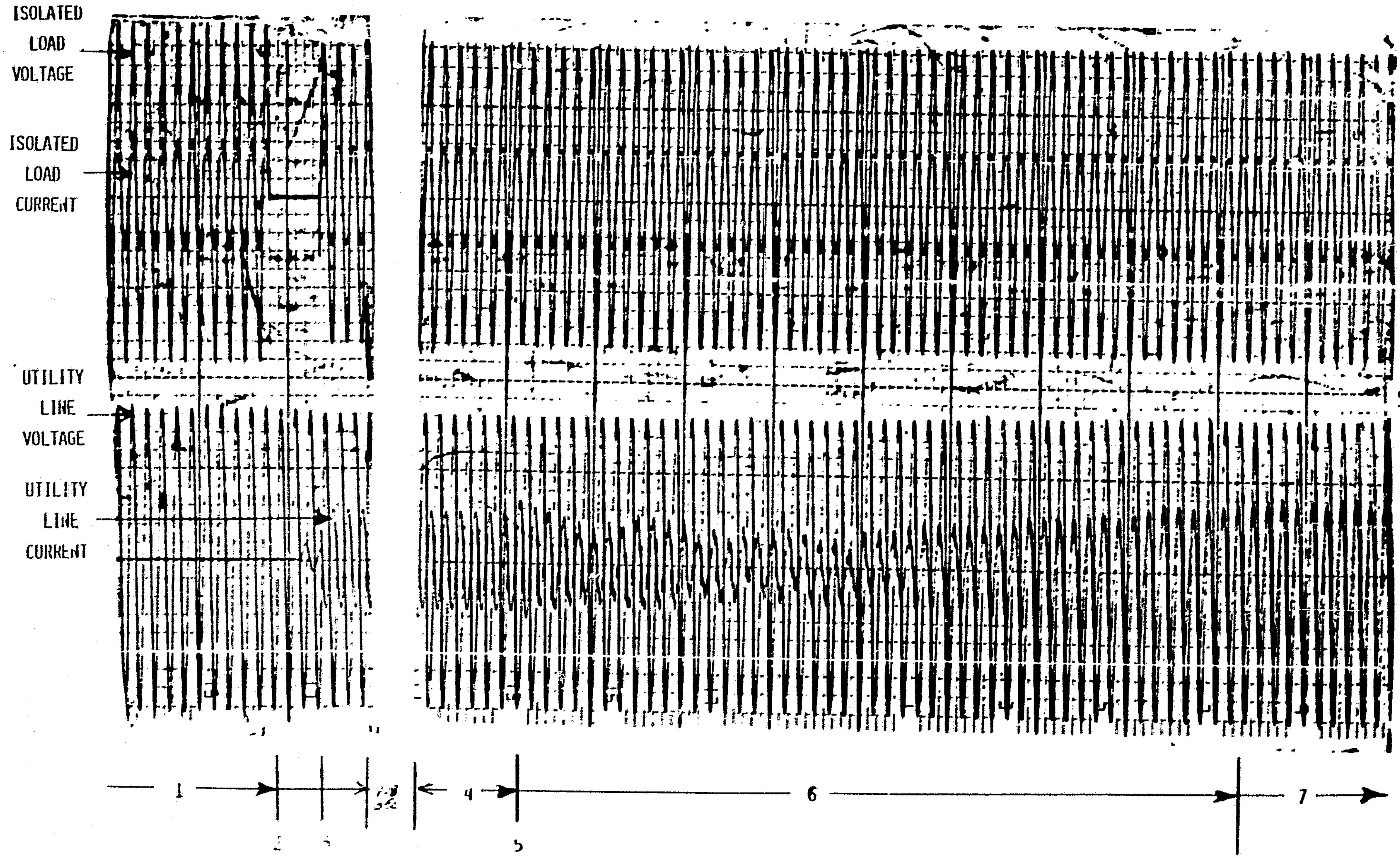
(4) WITHIN 2 SECONDS INVERTER SYNCHRONIZES WITH UTILITY LINE.

(5) SWITCH SW-1 CLOSES.

(6) GCU RAMPS UP TO DISPATCH LOAD SETTING OF 40 kW WITHIN ONE SECOND.

(7) GCU OPERATES STEADY STATE AT DISPATCH LOAD SETTING WITH 18 kW SUPPLIED TO ISOLATED LOAD AND 22 kW SUPPLIED INTO UTILITY LINE.

APPENDIX B-2 VISICORDER TRACE - ISOLATED MODE TO GRID CONNECT MODE



APPENDIX B-3

VISICORDER TRACE - PROTECTION LOW AC LINE DISCONNECT FROM UTILITY LINE AND AUTO RETURN TO GRID CONNECT AFTER LINE RETURNS TO NORMAL.

(1) GCU OPERATING IN GRID CONNECT MODE AT 40 kW DISPATCH WITH 18 kW ISOLATED LOAD CONNECTED. B-1, SW-1, AND SW-2 CLOSED, SW-3 OPEN.

(2) UTILITY LINE REDUCED (VARIACE) BELOW UV TRIP POINT, SW-1 OPENS AND INVERTER TURNS OFF.

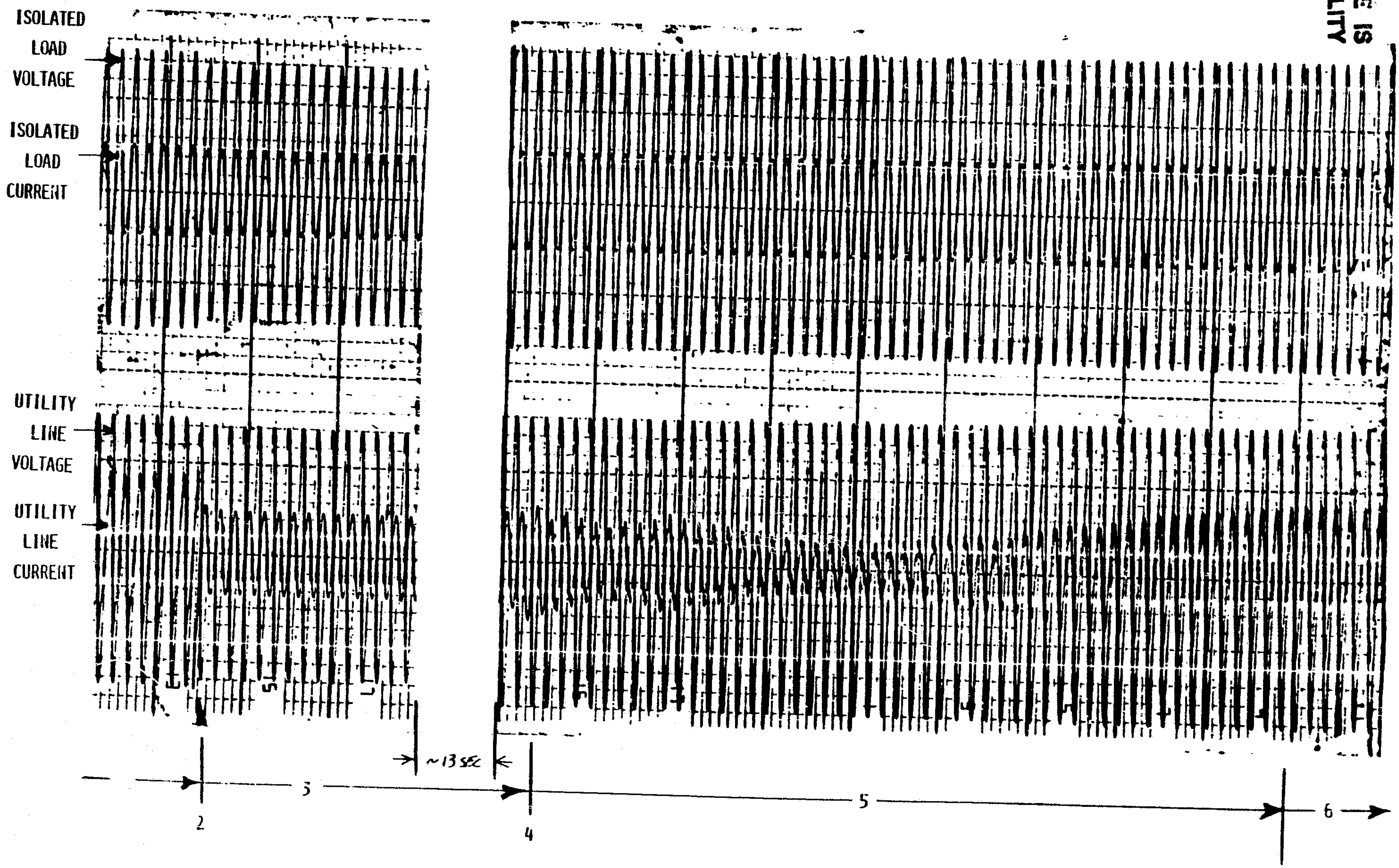
(3) INVERTER RESTARTS AND RUNS ON INTERNAL CLOCK. THE LINE WAS RETURNED TO WITHIN ± 5% OF RATED WITHIN 7½ SECONDS OF DISCONNECT. THE INVERTER SYNCHRONIZED WITH THE UTILITY LINE WITHIN 2 SECONDS WHILE GCU MONITORED "NORMAL" LINE FOR 5 SECONDS.

(4) GCU AUTOMATICALLY RETURNED TO GRID CONNECT.

(5) GCU RAMPED TO 40 kW DISPATCH LEVEL.

(6) GCU SUPPLIES 18 kW TO ISOLATED AND 22 kW TO LINE.

APPENDIX B-3 VISICORDER TRACE - PROTECTION LOW AC LINE DISCONNECT AND RETURN TO GRID CONNECT



APPENDIX B-4

VISICORDER TRACE - PROTECTION LOW AC LINE DISCONNECT FROM UTILITY AND AUTO TRANSFER TO ISOLATED MODE AFTER 30 SECONDS OF LOW LINE CONDITION.

(1) GCU OPERATING IN GRID CONNECT MODE AT 40 kW DISPATCH WITH 18 kW ISOLATED LOAD CONNECTED. B-1, SW-1, AND SW-2 CLOSED, SW-3 OPEN.

(2) UTILITY LINE REDUCED (VARIAC) BELOW UV TRIP POINT, SW-1 OPENS AND INVERTER TURNS OFF.

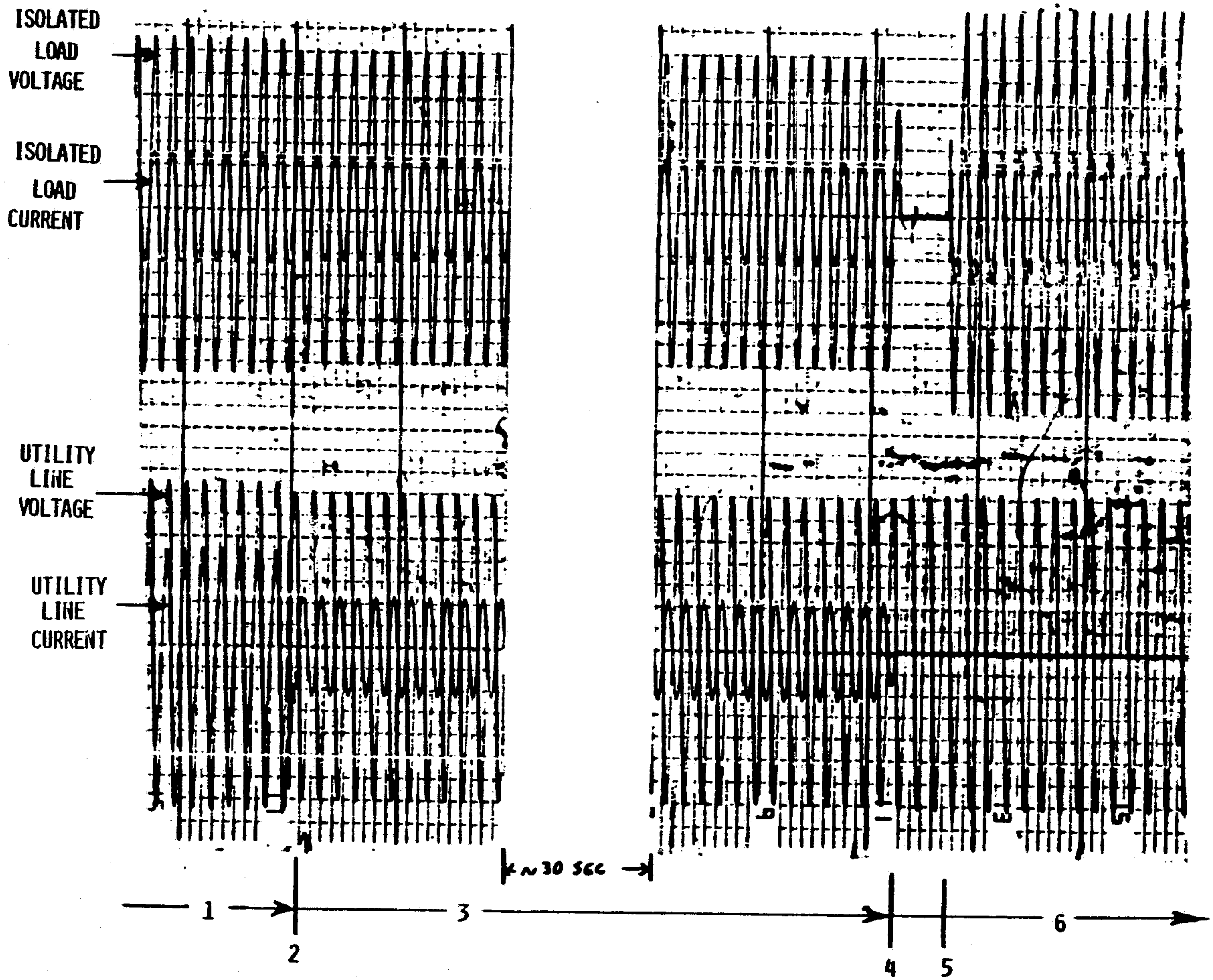
(3) INVERTER RESTARTS WITHIN 4½ SECONDS SYNCED TO INTERNAL CRYSTAL AND GCU MONITORS LINE VOLTAGE LEVEL.

(4) THIRTY SECONDS AFTER LINE GOES LOW AND DOES NOT RETURN TO NORMAL FOR AT LEAST 5 CONTINUOUS SECONDS, SWITCH SW-2 OPENS.

(5) 0.05 SECONDS LATER SW-3 CLOSES.

(6) INVERTER FURNISHES THE 18 kW ISOLATED LOAD.

APPENDIX B-4 VISICORDER TRACE - PROTECTION LOW AC LINE DISCONNECT AND AUTO TRANSFER TO ISOLATED MODE



APPENDIX B-5

VISICORDER TRACE - DISCONNECT ON LOSS OF LINE WITH DISPATCH LOAD SET EQUAL TO MOTOR LOADS AND AUTO RETURN TO GRID CONNECT UPON RETURN OF UTILITY LINE WITHIN 25 SECONDS.

(1) GCU OPERATING IN GRID CONNECT MODE AT DISPATCH LEVEL EQUAL TO 23 KVA ISOLATED LOAD INCLUDING MOTOR LOADS.

(2) DISCONNECT SW-4 MANUALLY OPENED.

(3) INVERTER CONTINUES TO RUN FOR 10 CYCLES.

(4) INVERTER TURNS OFF.

(5) MOTORS SLOW TO STOP WITHIN 15 CYCLES.

(6) SW-1 OPENS 4 CYCLES AFTER INVERTER TURNS OFF.

(7) SW-4 IS CLOSED PROVIDING UTILITY LINE TO GCU.

(8) MOTORS RESTART FROM UTILITY SUPPLY.

(9) INVERTER RESTARTS WITHIN 4½ SECONDS AND RESYNCHRONIZES WITH LINE. GCU MONITORS UTILITY LINE NORMAL FOR 5 SECONDS.

(10) SW-1 CLOSES.

(11) GCU RAMPS BACK UP TO ORIGINAL DISPATCH LEVEL.

APPENDIX B-5 VISICORDER TRACE - DISCONNECT ON LOSS OF LINE WITH DISPATH LEVEL SET EQUAL TO ISOLATED MOTOR AND RESISTIVE LOAD