650V DC Ride-Through System Ultra Capacitor Version

System Description and Test Results

TR-111919

Final Report, December 1998

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REPORT SUMMARY

Over the past decade, the need for effective short-term energy storage has become evident as a result of the sensitivity of modern equipment to power system disturbances. Adjustable Speed Drives (ASD) are some of the more sensitive electronic systems used in modern manufacturing facilities. The interruption of continuous processes due to the inability of the ASD to ride through voltage sags or momentary outages may lead to significant financial losses. This report describes an ultracapacitor version of a ride-through system developed by Maxwell Technologies.

Background

Most power quality problems are of very short duration and operators estimate that a five-second ride-through window would alleviate over 80% of process critical voltage incidents. For the ASD ride-through application, the energy storage is required to have high *power* density, but the required *energy* density is low. The ride-through system described in this report is based on Maxwell Technologies' Power Cache PC7223 ultracapacitor. This double-layer capacitor, incorporating a unique metal/carbon electrode and an advanced non-aqueous electrolytic solution, can be charged and discharged in excess of 100,000 times.

Objective

To develop and test an ultracapacitor based ride-through system for DC link applications.

Approach

The project team ran the ASD, connected to the ultracapacitor, under several different loads, opening the circuit breaker to simulate a total power interruption. They monitored the bus voltage and measured the ride-through duration. They also measured recharge time for various voltages and the input power at idle and during recharge of standby losses. They calculated average standby power based on the time duration of the charging period and the time between periods.

Results

Maxwell Technologies designed the system described in this report for voltage source adjustable speed drives and other DC link applications. They connected the ultracapacitor directly to the DC link, thereby avoiding the complexities and inefficiencies associated with conventional AC uniterruptible power supplies. This ultracapacitor delivers 500 kJ with ride-through time determined by the load. The sophisticated control system allows the operator to set the voltage trip level so that once energized; the system controller monitors the DC bus voltage and seamlessly starts supplying the load when low voltages breach the undervoltage trip level. When the outage or sag is cleared and the bus voltage restored to a suitable level, the system automatically stops supplying the load and switches to a charging mode of operation. Charging times are on the order of 20-30 minutes.

EPRI Perspective

Industrial processes contain the extensive use of power electronic equipment and are difficult to maintain with the existing electrical delivery systems. The effects of voltage sags, the natural characteristic of power delivery systems, can be mitigated with the use of supercapacitor systems. These systems provide a means to store energy and deliver it to the industrial load as required and so protect vital industrial production equipment from power quality events.

TR-111919

Interest Categories

Power electronics
Power conditioning
Motor and drive systems
Power quality

Keywords

DC drive ride-through
Ultracapacitors
Capacitors

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1

INTRODUCTION

As a result of the sensitivity of modern equipment to power system disturbances, the need for effective short term energy storage has become evident over the past decade. Adjustable Speed Drives (ASD) are some of the more sensitive electronic systems used in modern manufacturing facilities. The interruption of continuous processes due to the inability of the ASD to ride through voltage sags or momentary outages may lead to significant financial losses. Most power quality problems are of very short duration and it is estimated that a five second ride-through window alleviates over 80% of process critical voltage incidents.

Maxwell Technologies (Nasdaq: MXWL), headquartered in San Diego, has been an industry leader for over thirty years in high average and pulsed power systems, high energy electrical components, electronics and software solutions. Based on this heritage, Maxwell has leveraged its expertise in high power density energy storage technology to develop an ultracapacitor based ride-through system for DC link applications, as shown in Figure 1-1. The ride-through system is based on Maxwell Technologies' PowerCache™ PC7223 ultracapacitor, which is rated at 2.3 Volts and 2700 Farads and has a volume of approximately 0.6 liters. The PowerCache™ ultracapacitor is a double-layer capacitor incorporating a unique metal/carbon electrode and an advanced non-aqueous electrolytic solution; it can be charged and discharged in excess of 100,000 times.

Figure 1-1
Maxwell Technologies 100 kW ride-through system.

The system is designed for voltage source adjustable speed drives (and other DC link applications) and is connected directly to the DC link, as shown in Figure 1-2. This avoids the complexities and inefficiencies involved with conventional in-line or off-line AC uninterruptible power supplies. Connection to the DC bus can use the braking resistor terminals provided by the ASD manufacturer. No separate charger connection or logic power supply is required, all power is derived from the DC load bus. Maxwell's ultracapacitors have a very long holdup time and logic power requirements are not significant. Consequently, total standby losses of the 100 kW system are much less than 0.5% of rating, leading to a low cost of ownership. In addition to the two power terminals, the system provides for a connection to integrated contactors, which the user can slave to the ASD's emergency stop or to the breaker feeding the drive. This feature prevents a system discharge in case of drive failures or emergency stops.

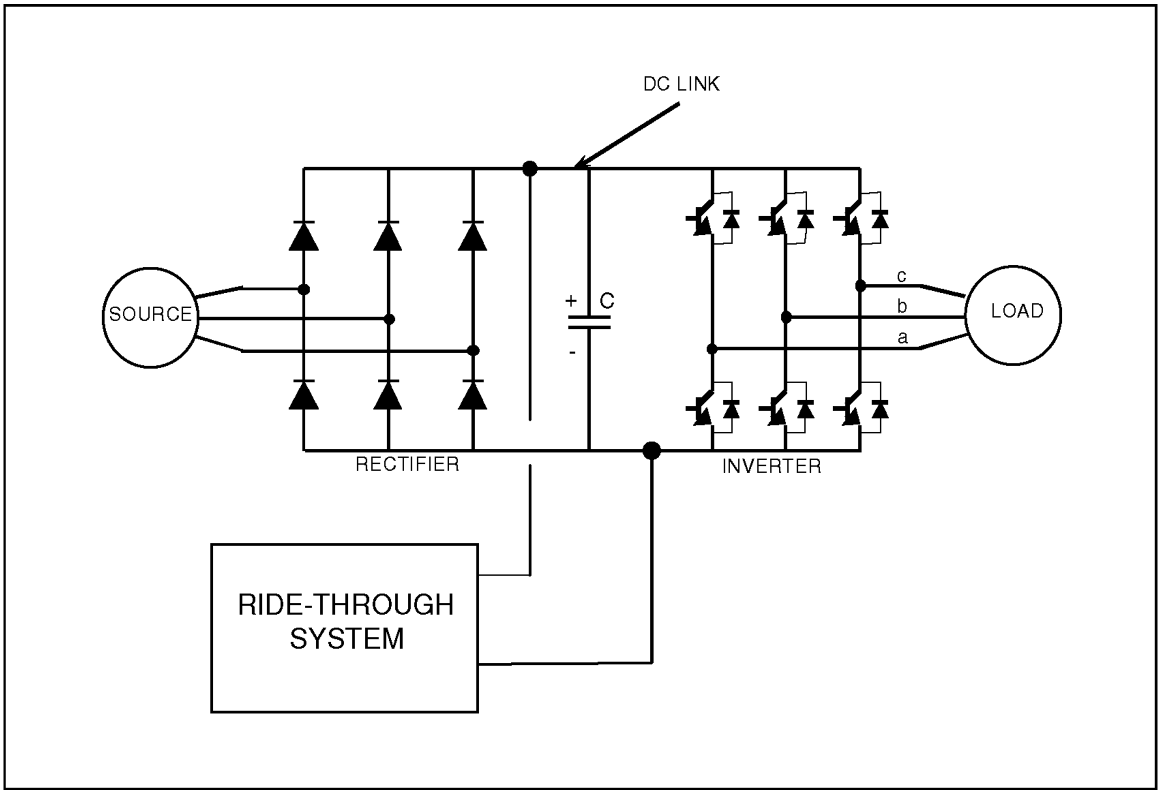

Figure 1-2
Illustration of how Maxwell Technologies ride-through system is applied to an adjustable speed drive.

Maxwell Technologies' ride-through system is designed to deliver 500 kJ; i.e., at the rating of 100 kW, the load is supported for 5 seconds. Lower loads will result in longer ride-through times. The power electronic regulator is controlled by a digital signal processor with a display/keypad for user interface. This allows for sophisticated control, thermal management and protection. System protection features include overvoltage, overcurrent, short circuit and overtemperature. The controller allows for user setting of voltage trip levels and ASD bus capacitance; a factory pre-adjustment ensures satisfactory operation for typical adjustable speed drive characteristics. Once energized, the system controller monitors the DC bus voltage and seamlessly starts supplying the load when the undervoltage trip level is breached. When the outage or sag is cleared and the bus voltage is restored to a suitable level, the ride-through system stops supplying the load and automatically switches to the charging mode of operation. Figure 1-3 shows a typical discharge at reduced load.

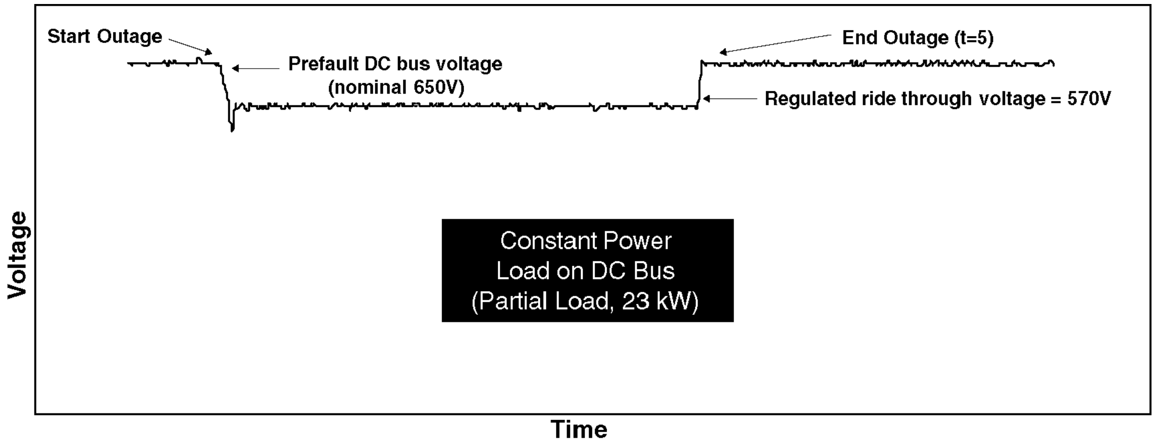

Figure 1-3
Ride-through system performance for 5 second outage.

Since the ultracapacitors are supplied directly from the DC bus, a trickle charge algorithm is employed to avoid overloading the drive rectifier stage; charging times are in the order of 20-30 minutes. Thermal management is based on an intelligent adiabatic algorithm and does not utilize any forced cooling. This enhances lifetime (no moving parts) and allows for many discharge scenarios within the thermal limits as determined in real time. Thus, the design requires very low maintenance.

This brochure describes the ultracapacitor version of the ride-through system. It is also available with advanced, high power density battery modules. Ride-through systems are available with a lead time of 8-12 weeks and a full scale demonstration site is available at Maxwell Technologies' San Diego facilities. Further information may be obtained by contacting Maxwell Technologies.

2

PRINCIPLES OF OPERATION

2.1 Introduction

Figure 2-1 shows a block diagram for the RTS100B-C Ride-Through System. For this application, a 480 V, three-phase adjustable-speed drive (ASD) is assumed. A passive rectifier generates the 650 VDC bus of the ASD. Eight ultracapacitor modules connected in series, each rated at 56 V, provide energy storage for the unit. The system uses a pair of switching DC-DC converters to charge and drain the ultracapacitor bank. During a voltage sag or interruption, the ultracapacitors supply power, and during charging, the ultracapacitors are trickle charged from the DC bus to avoid overloading the input rectifier of the ASD. The system is expected to respond in fractions of a cycle to a system load of up to 100 kW. The duration during which the system can support a load will vary inversely with the magnitude of that load.

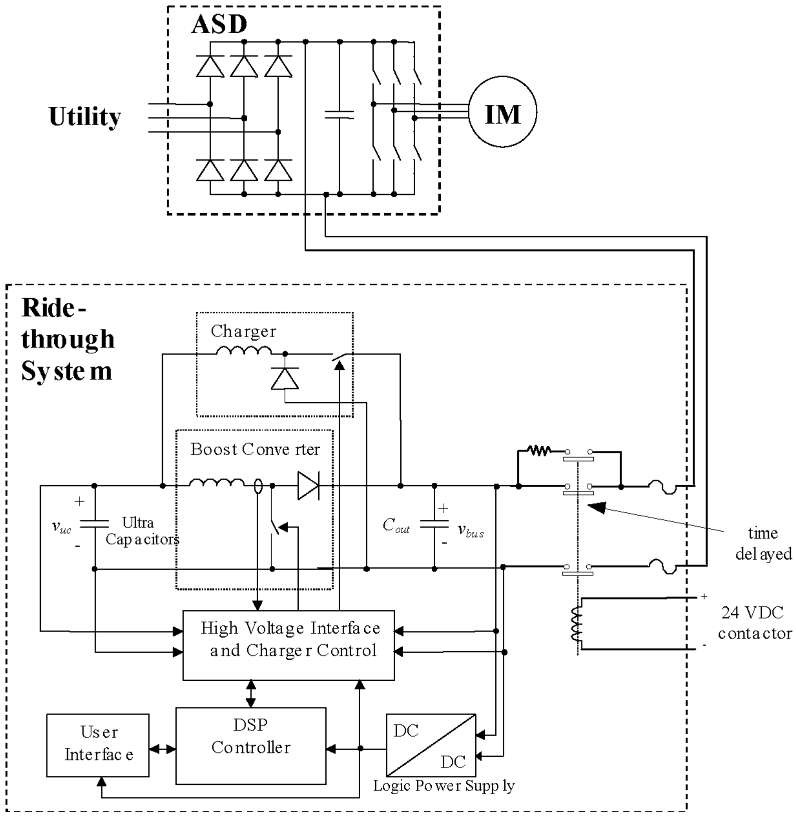

Figure 2-1
Block diagram for Ride-Through System.

2.2 Ultracapacitors

An essential component of the ride-through system is the energy storage. For the ASD ride-through application, the energy storage is required to have high power density, but in contrast to traditional energy storage systems, the required energy density is low. The energy storage system will also spend most of its life on standby and should have low standby losses. For this reason, Maxwell's PowerCache™ ultracapacitor is an ideal candidate as a source for energy storage. The ultracapacitor is a double-layer capacitor incorporating a unique metal/carbon electrode and an advanced non-aqueous electrolytic solution; it can be charged and discharged in excess of 100,000 times. Both batteries and ultracapacitors use liquid electrolytes; however, unlike batteries, ultracapacitors are not based on non-reversible electrochemical processes. Ultracapacitors behave like true capacitors; their stored energy is proportional to the square of their voltage. This makes it easy to determine the amount of energy stored in the system, and it allows for straightforward charging, monitoring, and control algorithms.

Because the voltage falls as the energy is removed from the capacitors, a DC-DC converter is needed to regulate the voltage to allow for ASD ride-through. There is also a trade off between the amount of energy available for ride-through and the rating of the power electronics used in the DC-DC converter. This trade off is the result of the increase in the capacitor current as the voltage drops while supplying constant power to the load.

2.3 Boost Converter

To maximize the efficacy of the ride-through system, it is crucial for the DC-DC conversion system to be as efficient as possible. To a lesser extent, it is important to maximize the efficiency of the conversion system to avoid the use of forced-air cooling. With the requirement that the converter regulates the bus voltage within one quarter of a 60 Hz cycle, and with the various efficiency requirements, a boost converter has been developed. The switching action in the boost converter is controlled directly via a fiber optic link from the digital controller board. The controller board implements a pulse-width modulation (PWM) scheme to control the boost converter. Isolated analog current and base plate temperature signals are also provided to the controller from the converter.

2.4 Charger

In conjunction with the boost converter mentioned above, a second DC-DC converter transfers energy to the ultracapacitors when necessary. The charging circuit is built as a current-controlled buck converter. Overcurrent protection and ultracapacitor overvoltage protection are also part of the charging circuit. The buck converter is designed to charge the capacitor bank slowly, so that the system will not draw excessive current from the DC bus during normal operation, thus damaging the drive's input rectifier. Further, since the charger draws such low current, relatively large heat sinks can be avoided, and forced-air cooling becomes unnecessary.

2.5 User Interface

The user interface consists of a two line, 20 character per line display. The display also consists of a 10 push button keypad allowing the user to change user definable parameters and monitor relevant signals. The display is interfaced to the DSP controller through an RS-232 interface.

2.6 Logic Power Supply

The logic power to the system is provided from the DC bus via a DC-DC converter. This converter consists of an isolated, unregulated, 650-50 V converter in a half bridge configuration. The unregulated 50 V output is regulated to ±15 V and 5 V via secondary DC-DC converters.

2.7 Controller

A digital controller board provides the primary control for the ride-through system. The controller board is powered by a digital signal processor (DSP), and it has the analog sensors, optocouplers, and fiber optic channels necessary to interface with the boost converter, the charger, and a user interface. Figure 2-2 shows a block diagram for the digital controller board.

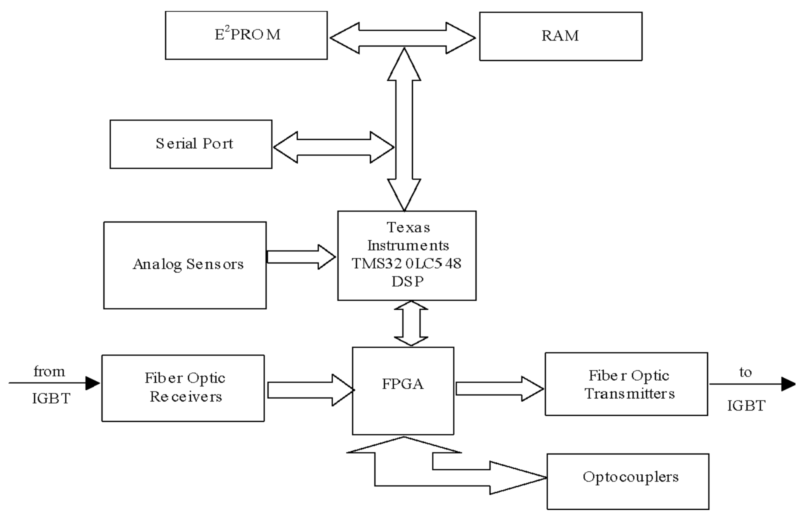

Figure 2-2
Block diagram of digital controller board.

The first task for the board is to monitor each bus and determine what action, if any, must be taken during each sampling period. If the ultracapacitors are not sufficiently charged, the controller will enable the constant-current charger if the output bus voltage is in its normal range. When the ultracapacitors are charged, the output voltage is monitored for sags or outages. If an event is then detected, a control loop is closed around the bus voltage, and the boost converter is enabled. The boost converter is controlled by a proportional-integral (PI) loop closed around the normalized output voltage error.

Since the PI loop will always have some error at the start of any outage or sag below the setpoint, it is important to select the setpoint in such a manner that the minimum resulting bus voltage will not lead to an ASD trip.

Examination of a typical system response can help explain how the system works. Figure 2-3 shows the response of the system to an outage while supporting a 50 kW constant power load. The voltage briefly dips below the setpoint while the control adjusts to the load, and the system brings the bus voltage back to the setpoint level. In this example, the bus voltage drops roughly 20 V below the 585 V reference before recovering. The user must take this brief dip into consideration when dialing in a reference voltage.

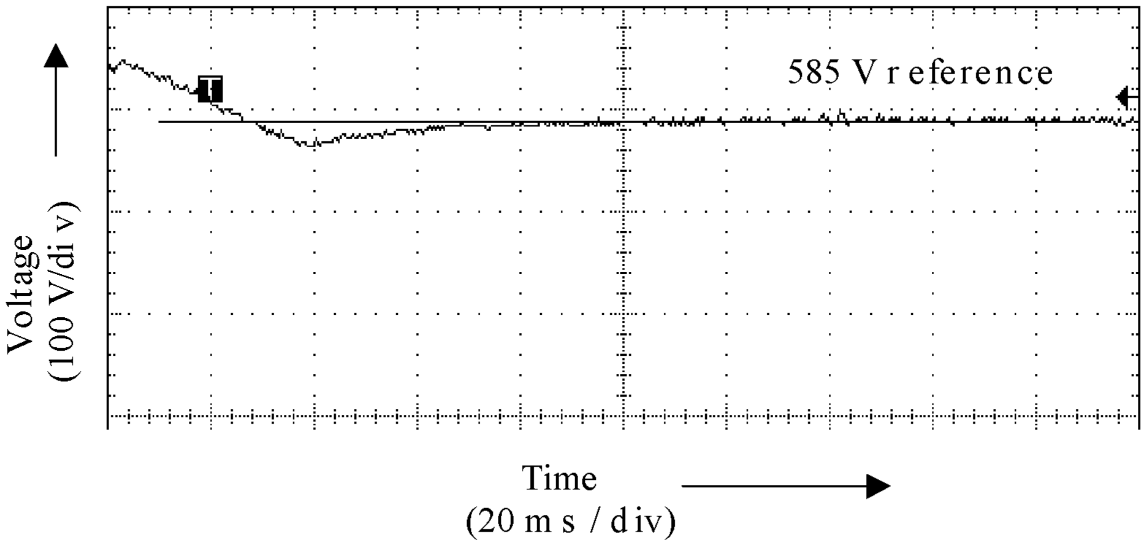

Figure 2-3
System response to a outage while a 50 kW load.

Another issue of interest covers the response of the system to bus recovery. Figure 2-4 shows the system response to a brief outage while serving a 50 kW load. Both the initial and final transients are quick, and there is no overshoot when the bus recovers.

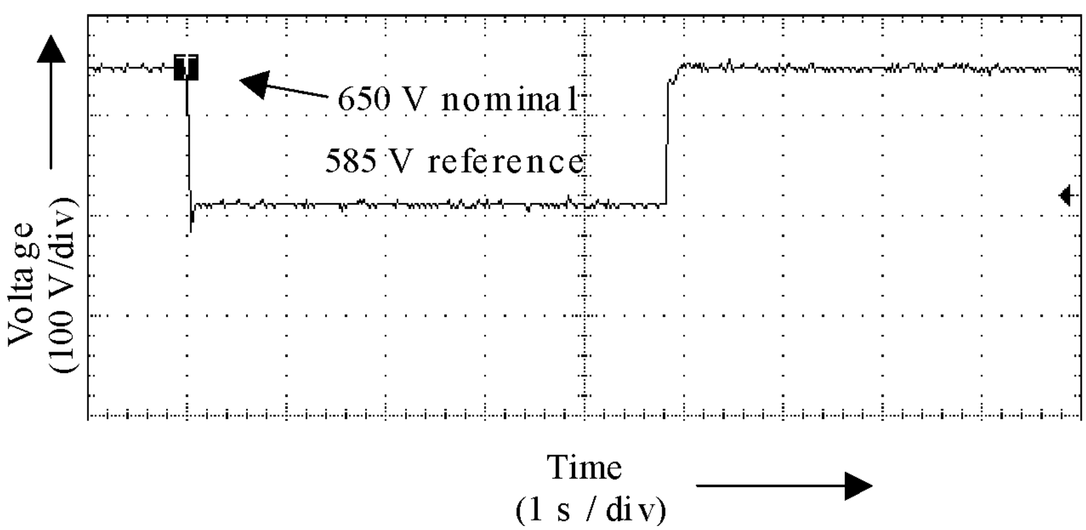

Figure 2-4
System response to a brief outage while supporting a 50 kW load.

2.8 Protection

To protect against catastrophic failure, a number of safety features are employed in both the controller and the components. This includes ultracapacitor overvoltage at the component as well as the stack level, overcurrent, and overtemperature protection. Warning or error messages appear when relevant.

3

SPECIFICATIONS

3.1 Configuration

Two terminal DC voltage source with integrated charger; logic power generated internally

3.2 Specifications (T_A = 25 °C, V_{OUT} = 585 VDC):

Output Power:	0 - 100 kW (0 – 135hp)
Ride Through Time:	5 seconds (at peak power rating). See Figures 3-1 and 3-2 for ride-through time vs. output power.

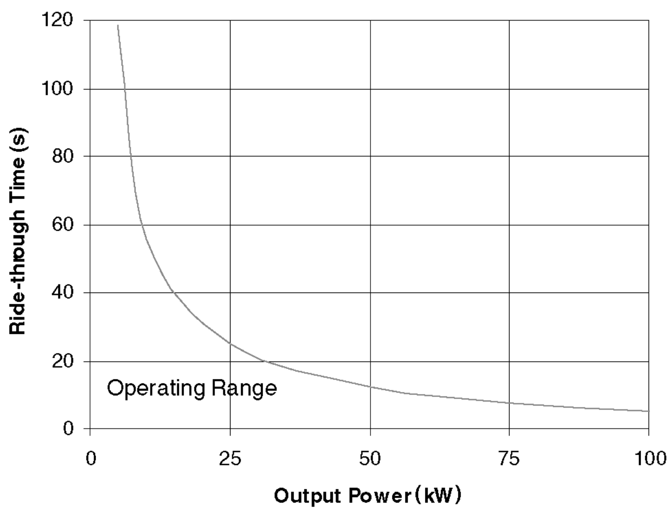

Figure 3-1
Ride-through time specification (0 to 100 kW).

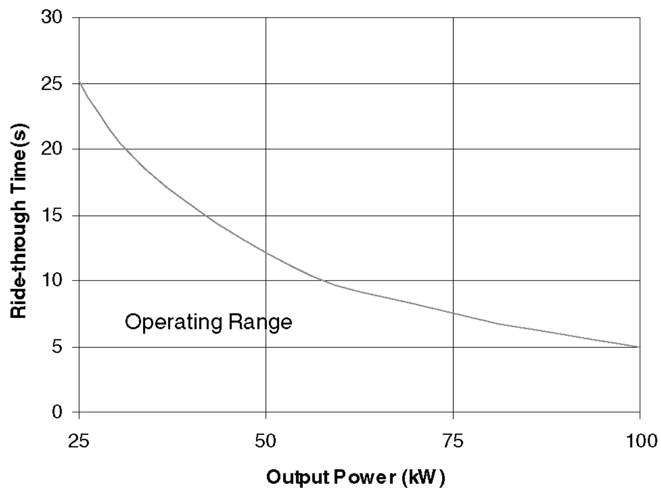

Figure 3-2
Ride-through time specification (25 to 100 kW).

Output Voltage During Sag:	455 to 615 VDC user adjustable (factory preset at 585 VDC)		
Output Voltage Accuracy:	1%		
Output Current:	175 A		
Nominal ASD Bus Voltage:	650 VDC		
Standby Power:	<u>min (W)</u>	<u>max (W)</u>	<u>avg (W)</u>
Logic	100	100	100
Charging	0	1000	100
Total	100	1100	200
Charge Time:			
Initial Charge	1 hr		
Re-Charge	30 minutes maximum		
Load Requirement:	Capacitive, 100 μF/kW minimum		
Control:	Digital Signal Processor		
Protection:	Overvoltage, overcurrent, short circuit, overtemperature, emergency trip via user input		

3.3 Environmental

Enclosure:	Drip proof, indoor installation
Cooling:	Natural convection, do not place unit in direct sunlight
Ambient Operating Temperature:	0 to 40°C
Ambient Storage Temperature:	–25 to 70° C
Humidity:	0 to 95% non-condensing
Altitude	Sea level to 3,000 meters

3.4 Physical

Base:	$23^{5}/_{8}$” x $31^{1}/_{2}$” (60 cm x 80 cm)
Height:	67” (170 cm)
Weight:	1200 lb (550 kg)

(Beta units are packaged in a dual rack configuration with a base of 118 cm x 80 cm and height of 155 cm)

3.5 User Interface

Display:	Backlit LCD Alphanumeric 2 Lines x 20 Characters
Keypad:	Membrane keypad with tactile response

3.6 24 VDC User Controllable Disconnect

Source Voltage	
Normal operating range	18 to 36 VDC
Normal hold range	14 to 36 VDC
Relay Operation	
Pickup Voltage	18 VDC max
Dropout Voltage	10 VDC min

Source Current (average DC)	
Pickup	6.0A max (200 ms maximum pulse width)
Hold	1.0A max
Source Power	
Pickup	216W max (200 ms maximum pulse width)
Hold	14 W max

4

SYSTEM TESTS

4.1 Test Setup

Figure 4-1 is a photograph of the load test setup used during testing. The test setup for the load consists of a Circuit Breaker (1), 150 hp ASD (2), 150 hp Induction Motor (3), 150 hp Regenerative DC Drive (4), and a 150 hp DC Motor (5). In the setup the Induction and DC motors are coupled together at the shaft. The DC drive provides the load to the ASD. The regenerative nature of the DC drive results in the power supplied to the ASD being fed back into the utility. The secondary circuit breaker (1) allows for disconnection of the ASD from the utility without removing the load. The schematic diagram in Figure 4-2 illustrates the connections in more detail.

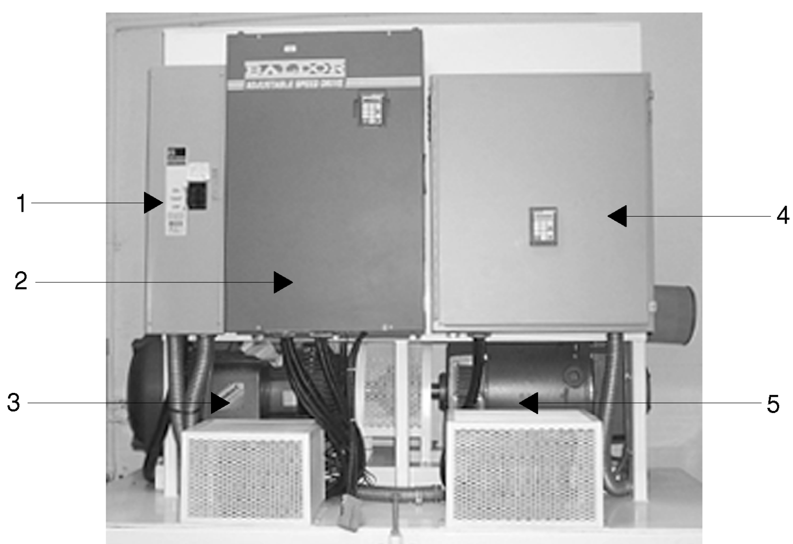

Figure 4-1
Load test setup.

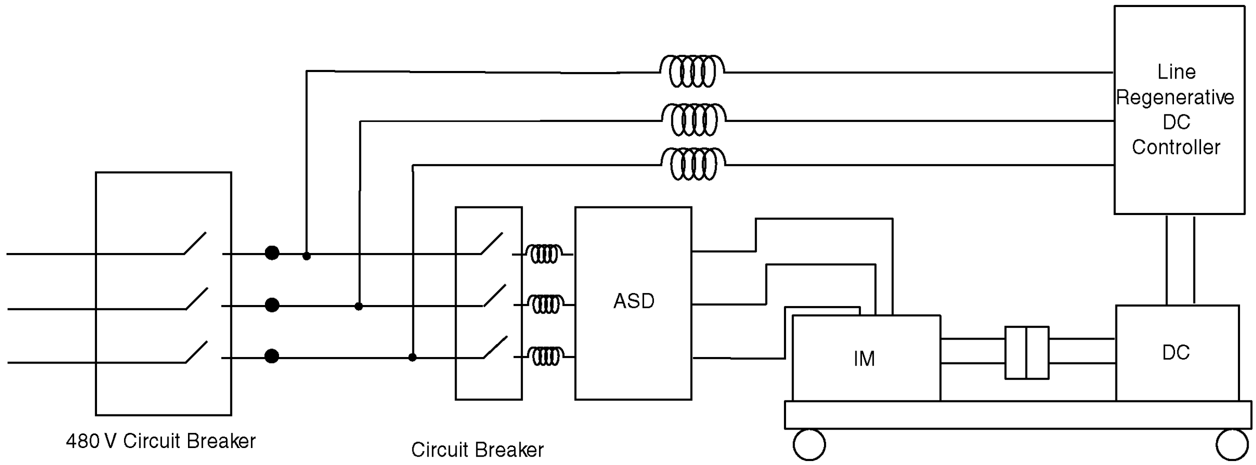

Figure 4-2
Load test setup block diagram.

4.2 Test Setup Specifications

ASD

Model:	Baldor ID15H4150-EO
Serial #:	1398RX071
Power:	150 hp
Input:	4/60 VAC, 3ph, 50/60 Hz
Output:	0 to 460 VAC, 3ph, 0 to 400 Hz

Induction Motor

Model:	Baldor M44061-4
Serial #:	1197C
Power:	150 hp
RPM:	1785
Volts:	460 VAC

Amps:	160A
Hz:	60

DC Drive

Model:	Baldor BC20H4150-CL
Serial #:	98RX413
Power:	150 hp
Input:	460 VAC, 3ph, 50 / 60 Hz
Output:	500 VDC, 270 A
Field:	0 to 15 Amps

DC Motor

Model:	Baldor D50150P-BV
Serial #:	N097 / 0266-971030-19
Power:	150 hp
RPM:	1750 / 2000
Arm. Volts:	500
Arm. Amps:	240
Field Volts:	150 / 300
Field Amps:	6.06-4.94 / 3.03-2.47

4.3 Test Data

The test results are based on the following operating conditions

Ambient Temperature:	25°C
Bus Voltage Set Point During Outage:	585 VDC
Ultracapacitor Charge Voltage:	444-448 VDC
Test Unit:	Maxwell RTS100B-C
ASD Bus Capacitance:	10,000 µF

4.4 Ride-Through Time vs. Output Power

The ASD was run under load and the circuit breaker was opened simulating a total power interruption. The bus voltage was monitored using an oscilloscope and the ride through duration was measured. This procedure was repeated for several different loads. A plot of the measured ride-through time vs. load is given in Figure 4-3. Figure 4-4 illustrates the 25-100 kW range in more detail.

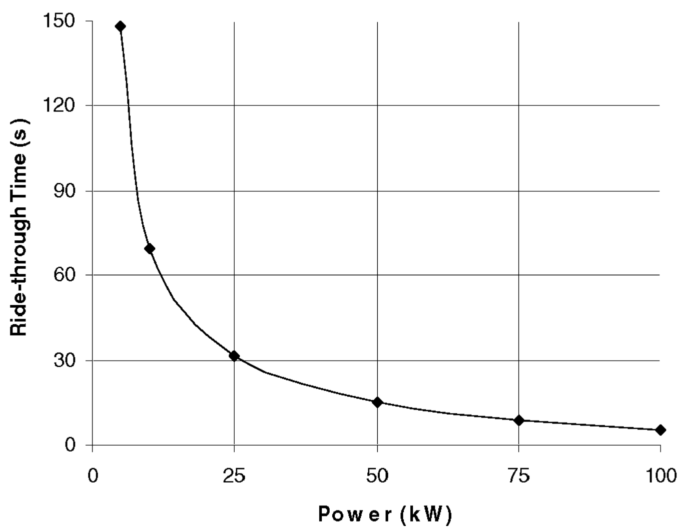

Figure 4-3
Ride-through time vs. output power (0-100 kW).

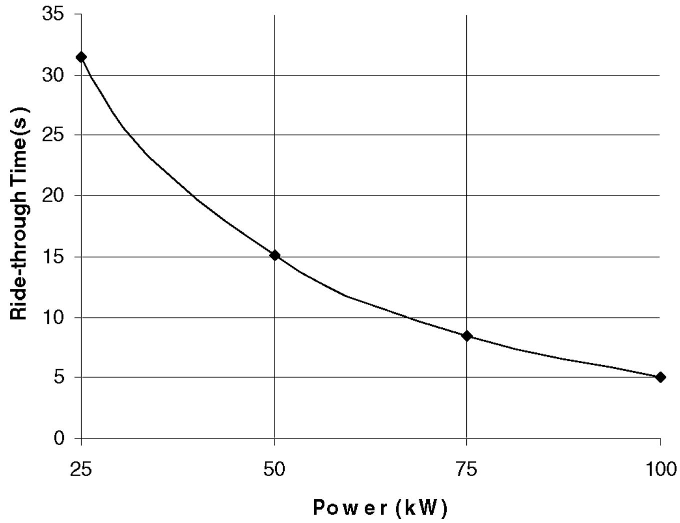

Figure 4-4
Ride-through time vs. output power (25-100 kW).

4.5 Recharge Time vs. Ultracapacitor Voltage

After being fully discharged, the ultracapacitor bank was completely recharged with a charging current of 2A. A voltage measurement was taken at 5 minute intervals until the bank reached full charging voltage (448 VDC). From this data, the recharge time was calculated for various voltages. A plot of the recharge time vs. ultracapacitor voltage is given in Figure 4-5.

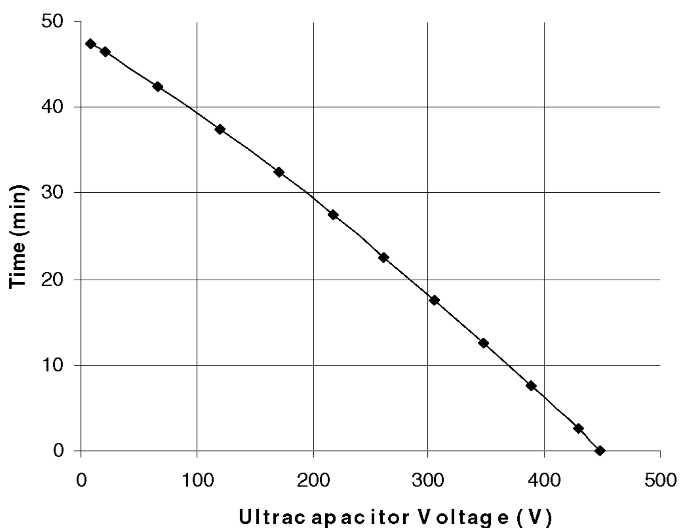

Figure 4-5
Recharge time vs. ultracapacitor voltage.

4.6 Recharge Time after Full Ride-Through vs. Supported Load

The power electronics of the system and the equivalent series resistance (ESR) of the ultracapacitors limit the amount of energy that can be removed from the ultracapacitors. This limit is load dependent. Because the remaining stored energy in the ultracapacitors depends on the load, the re-charge time is also load dependent. A plot of the recharge time after full ride-through vs. the supported load is given in Figure 4-6. Full ride-through refers to extracting energy for the maximum time at any given load. (NOTE: the ride-through system will respond to an outage even if the ultracapacitors are only partially recharged; however, the ride-through time will be reduced.)

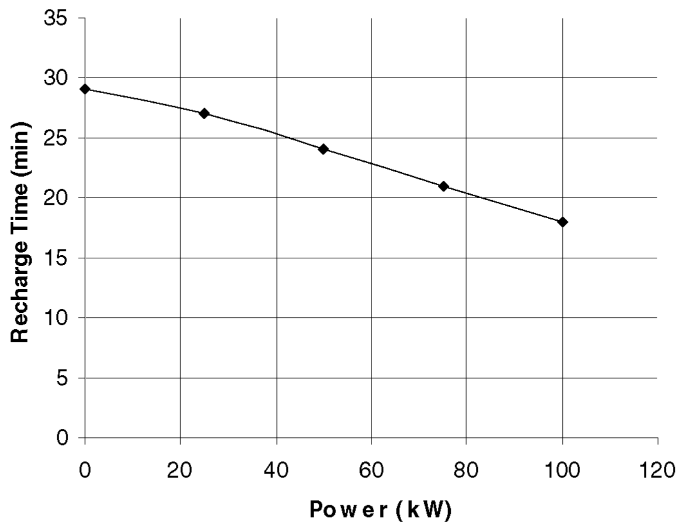

Figure 4-6
Recharge time after full ride-through vs. supported load.

4.7 Standby Power

Under float, in addition to logic power requirements, the ultracapacitor charger will turn on for short periods of time to recharge any standby losses in the ultracapacitors. The input power was measured at idle and during this charging period. The time duration of the charging period and the time between periods was also measured. Based on this, average standby power can be determined.

Measured RTS Input power:

Idle	70 W
Charging	1 kW

Charge and idle times measured are given in Table 4-1 for 4 consecutive cycles after initial charge

Table 4-1
Ultracapacitor standby recharge cycle at standby.

Charge Time(s)	Idle Time(s)
27	510
25	559
23	588
24	610

The total average standby power is (worst case):

$$\underbrace{1000W * 27s / 537s}_{\text{standby ultracapacitor recharge}} + \underbrace{70W * 510s / 537s}_{\text{logic power}} = \underbrace{117W}_{\text{total average standby power}}$$

4.8 Transient Responses

Figure 4-7 shows the response of the system to an outage of approximately 3 seconds while supplying a 100 kW load. The Figure shows a quick recovery of the DC bus by the RTS after the outage and minimal overshoot after the 3 phase input voltage is reapplied.

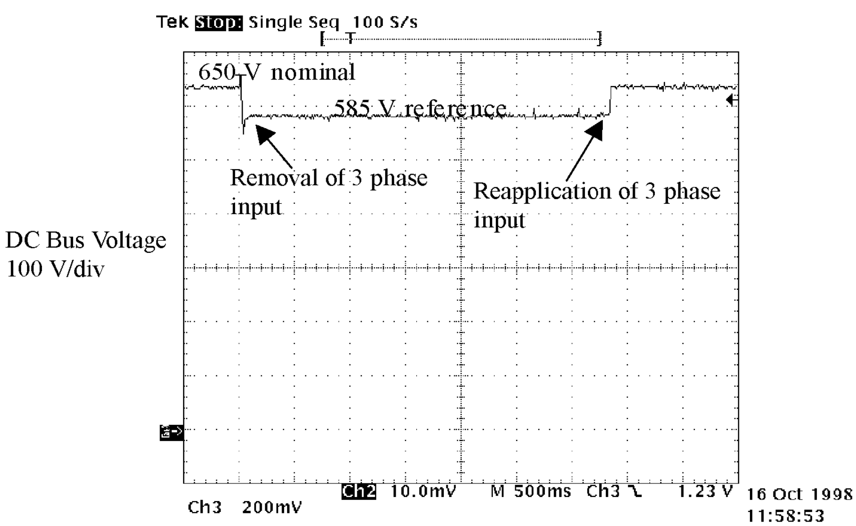

Figure 4-7
System response to 3 second outage (100 kW load).

Figure 4-8 shows the transient response of the system to an outage while supporting a 100 kW load. The response shows that the system will regulate to 1% of the reference voltage within 20 ms. The response also shows the initial dip in the bus voltage below the set point. This dip is roughly 40 V (7%) for a 100 kW load.

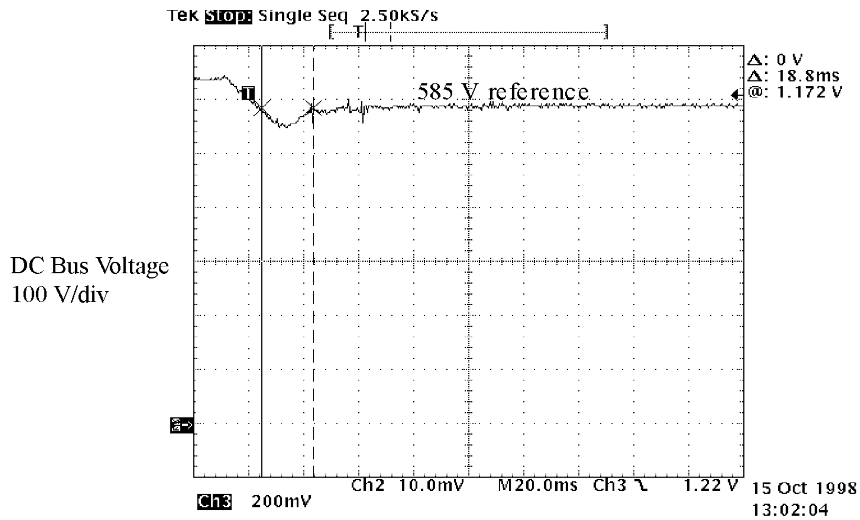

Figure 4-8
System transient response (100 kW load).

Figures 4-9 and 4-10 show the ride-through times for 100 kW and 50 kW loads, respectively and illustrate the quick recovery of the DC bus by the RTS after the outage. At the end of the ride-through period, a deep dip in the regulated voltage is evident, followed by a recovery of the voltage. This dip is caused by the RTS reaching its energy limit for the given load. Subsequently, the DC bus voltage falls quickly to a point where the ASD trips from bus undervoltage. Following the ASD trip, the load is removed and the RTS once again regulates the DC bus to the set point, with minimal overshoot for this no load condition. The cursors on the plot mark the ride-through period for the given load.

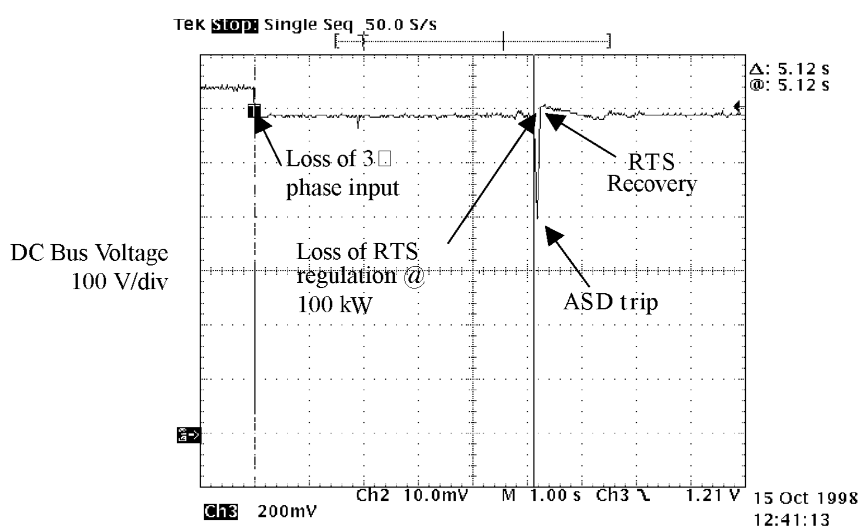

Figure 4-9
System ride-through at 100 kW.

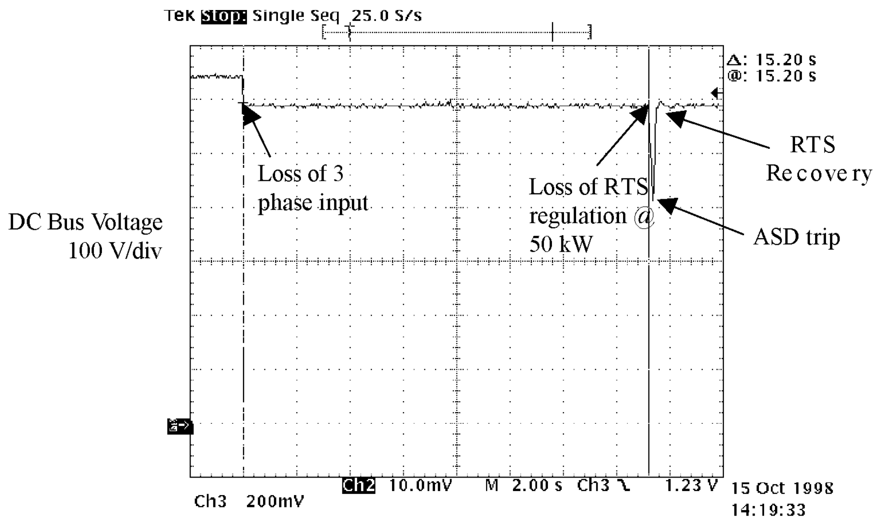

Figure 4-10
System ride-through at 50 kW.