Application Note
AN-0003

OzPCS-RS40 Seamless Transfer System Configuration

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ABSTRACT

The OzPCS-RS40 is a 40kW Power Conversion System (PCS) intended for battery-based energy storage applications. The OzPCS-RS40 can operate in both grid-following mode, sourcing or sinking power to and from the utility; as well as grid-forming mode, in which it will form a 3-phase AC output to support real and reactive loads. This application note describes the basic system configuration recommended for seamless transfer between operating modes.

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1. Introduction

The ability of an Energy Storage System (ESS) to operate in both grid-forming as well as grid-following modes provides greater customer value than traditional grid-tie only systems. (Note that for the purposes of this document, “grid-following” and grid-tie” are synonymous.) When the grid fails, a system that seamlessly reconfigures itself for voltage forming mode, and automatically provides backup support of critical loads, provides the customer a more robust, resilient, and secure energy solution. The OzPCS-RS40 PCS includes advanced control features that allow it to seamlessly transfer between the two operating modes. When used in conjunction with a utility interconnection relay, multiple OzPCS-RS40s can be operated in parallel, providing a scalable, robust solution.

This application note is intended to help system engineers design and configure resilient Energy Storage Systems using the OzPCS-RS40. It provides recommendations for control hardware, software settings, and operational logic. The document assumes a basic understanding of the components and functionality of an ESS, as well as basic PCS functionality.

2. Safety

The information contained in this application note is intended be used in conjunction with other product and safety documentation provided by Oztek. It is assumed readers are familiar with high-voltage/high-power systems and the general safety considerations related to the wiring and use of 3-phase AC electricity, battery systems, and PV energy sources. Oztek strongly suggests that a qualified engineer be engaged to do detailed system design and ensure conformance with local codes. UM-0061 should be consulted for OzPCS-RS40 product specifications upon which to base any detailed designs.

⚠ **CAUTION**

This document does not purport to make recommendations regarding conformance with applicable electrical codes. Oztek highly recommends engaging a utility interconnection representative as early as possible in the design of any product involving an electrical island for backup power, to determine local utility interconnection requirements as an Authority Having Jurisdiction. This application note is provided as-is, with no warrants that the system described herein will be approved by a utility. Actual transfer times to back-up power may be dependent on utility interconnection requirements. Oztek is not responsible for design and implementation of hardware, control, or safety systems outside of the OzPCS-RS40.

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3. System Architecture and Operation

Figure 1 provides a one-line illustration of an overall ESS system configuration using multiple OzPCS-RS40s. The system controller typically provides some combination of the battery management system (BMS) and energy management system (EMS) functions, controlling the charge and discharge of the ESS. A utility interconnection relay is used to monitor the utility's voltage and frequency status. An uninterruptable power supply (UPS) provides local backup power to the controller and relay should a grid fault occur. The grid interface contactor provides a means to isolate the critical load microgrid from the main grid during grid fault conditions. Lastly, a means to shed non-critical loads can be included to improve up-time.

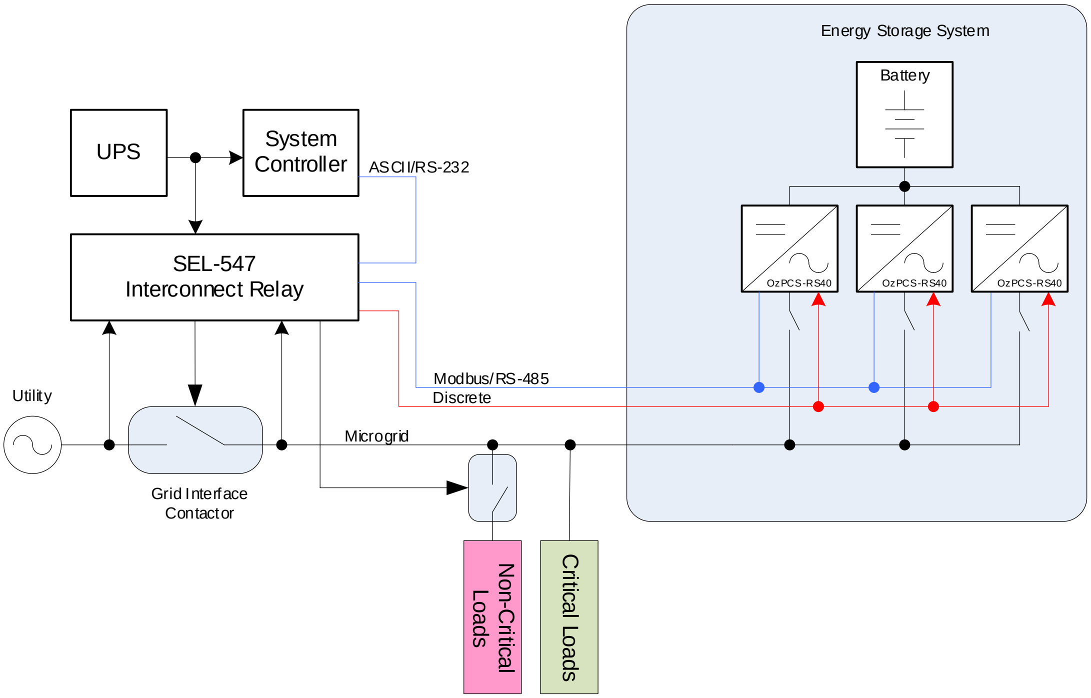

Figure 1 – System Block Diagram

3.1 Utility Interconnect Relay & Contactor

When used in grid-following only applications, the OzPCS-RS40 provides all the necessary interconnection and safety features required by UL1741. These features include anti-islanding, which prevents the PCS from energizing a dead electrical grid. In these applications a utility interconnect relay is not required.

However, in systems that require both grid-following and grid-forming operating modes, the PCS's anti-island algorithm must be disabled to allow it to power the local micro-grid. In these applications a utility interconnection relay and grid interface contactor are added to the system implementation. The relay provides conformance with utility interconnect requirements, such as IEEE-1547, at the Point of Common Coupling (PCC), by controlling the grid interface contactor. These control signals are also used to transition the PCS between grid-following and forming modes. Common utility interconnect relays include those listed in Table 1. All testing performed by Oztek utilized the SEL-547 device. Please note that while the SEL-547 device is still available, the SEL-751 is recommended for new designs.

Table 1 - Utility Interconnection Relays

Company	Model	Link
Schweitzer Engineering Laboratories	SEL-547	https://selinc.com/products/547/
	SEL-751	https://selinc.com/products/751/
Basler Electric	BE1-11i	https://www.basler.com/Product/BE1-11i-Intertie-Protection-System

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CAUTION

System designers should inquire with their local utility to validate conformance of the SEL-547, SEL-751, or BE1-11i to local Authority Having Jurisdiction requirements. Oztek cannot guarantee either device will be accepted for interconnection by your local utility.

3.2 Grid-Following Mode

Under normal conditions the grid interface contactor is closed, and the PCS operates in grid-following mode, responding to real (P) and reactive (Q) power commands from the system controller. In this mode the PCS also provides UL1741 smart inverter grid support functions such as Volt/VAR, Volt/Watt, and Freq/Watt.

When the SEL-547 detects abnormal grid conditions it will open the grid interface contactor, disconnect non-critical loads, and assert the discrete input to the PCS. Upon assertion, the PCS will seamlessly transition from grid-following to grid-forming mode.

3.3 Grid-Forming Mode

Once in grid-forming mode, the PCS operates as a 3-phase voltage source, actively regulating the voltage and frequency of the micro-grid. In this mode the PCS responds to voltage and frequency setpoint commands from the system controller rather than the power setpoints used in grid-following mode. Note that the OzPCS-RS40 employs droop control techniques which allow multiple PCS to be paralleled to share the load.

While in grid-forming mode, the SEL-547 continuously monitors the utility voltage and frequency to determine if they have returned within acceptable ranges for five (5) minutes. When the utility returns within the normal voltage and frequency operating ranges, the SEL-547 will wait until the utility and micro-grid comply with the IEEE-1547 synchronous interconnection criteria: voltages within 10%, frequency within 0.3 Hz, and phase angle less than 20°. Once these conditions are met, the SEL-547 will close the grid interface contactor, reconnect non-critical loads, and de-assert the discrete input to the PCS. When the input is de-asserted, the PCS will seamlessly transition from grid-forming mode back to grid-following mode.

3.4 Grid-Forming Only Mode

In rare instances it may be of value to operate the PCS in grid-forming mode whether the utility is present or not. In these applications there is no need for the discrete control wire between the SEL-547 and the PCS, as the PCS will never be operated in grid-following mode. The PCS can either be enabled in grid-forming mode while the grid is present, or black started if it is not. Once enabled and operating, the SEL-547 handles connecting and disconnecting from the utility as described above.

4. Electrical Interface Schematic

The schematic shown in Figure 2 illustrates a typical hardware implementation using the SEL-547, a grid interface contactor, and the OzPCS-RS40. This configuration was used for the testing documented in this application note. For parallel test cases described below, three PCS's were operated in parallel as shown.

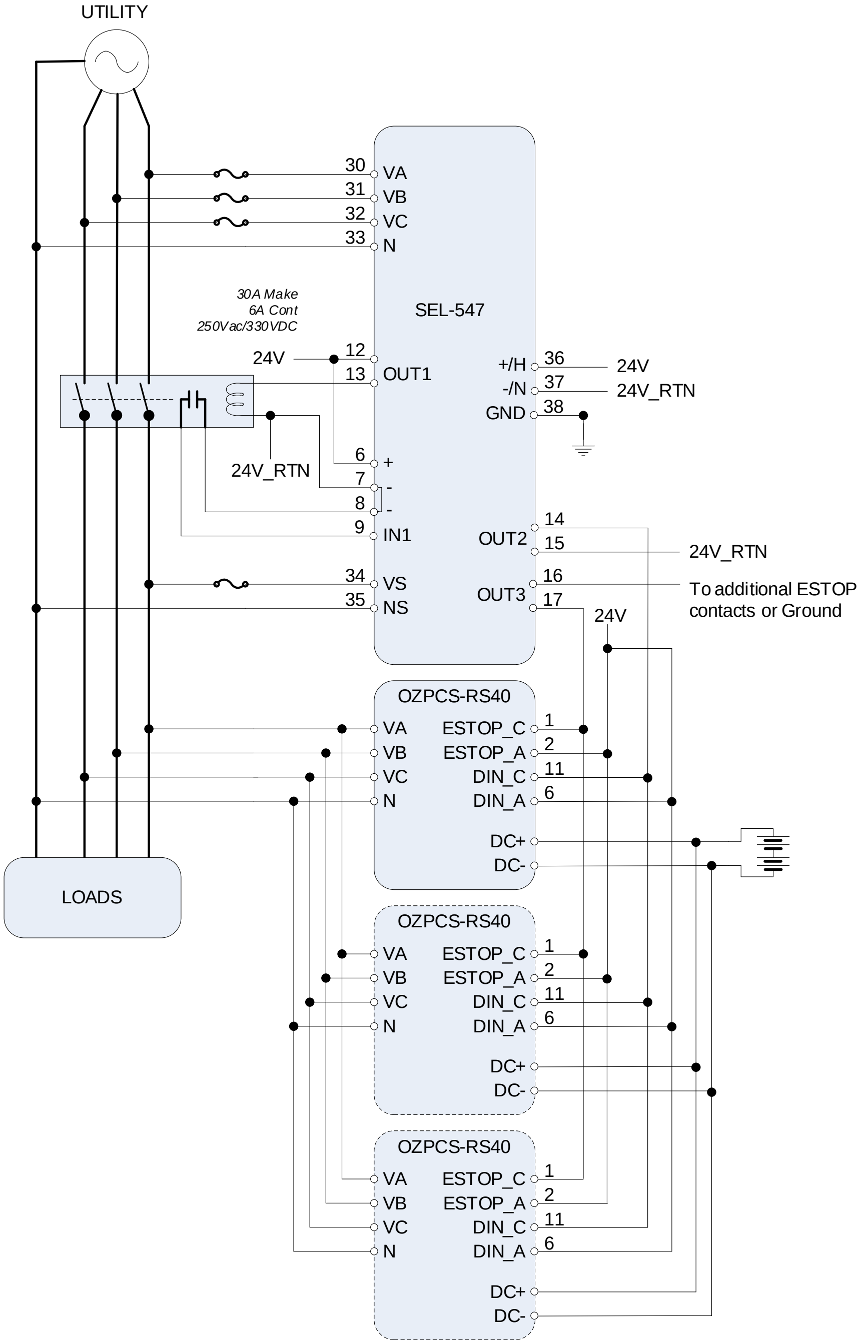

Figure 2 – Electrical Interface Schematic

5. SEL-547 Configuration Settings

5.1 Protection Functions

The SEL-547 provides a variety of relay protection elements, including voltage, synchronism check, frequency, and power elements. Table 2 lists the recommended SEL-547 EZ Settings for a typical 480Vac/60Hz application. Note that the SEL-547 protection functions are grouped by function numbers, e.g., 27 used to check for under-voltage, 59 for over-voltage, 81 for over/under-frequency, and 25 for synchronization checks (island versus grid).

Table 2 - EZ Settings Summary

ID	Description	Default Setting	Recommended Setting
CRATIO	Current Transformer Ratio	80	n/a
NOMV	Nominal Line to Line Voltage (208-480VAC)	208	480
3PCONN	Voltage Connection	WYE	WYE
FREQ	Nominal Frequency	60	60
ROTATE	Phase Rotation	ABC	ABC
	Voltage Monitor Settings		
27UV1P	Under Voltage 1 (OFF, 50-100%)	50	80
27UV1D	Under Voltage 1 Time Delay (0-16000 cyc)	6.00	0.00
27UV2P	Under Voltage 2 (OFF, 50-100%)	88	88
27UV2D	Under Voltage 2 Time Delay (0-16000 cyc)	116.00	120.00
59OV1P	Over Voltage 1 (OFF, 50-100%)	110	108
59OV1D	Over Voltage 1 Time Delay (0-16000 cyc)	56.00	120.00
59OV2P	Over Voltage 2 (OFF, 50-100%)	120	110
59OV2D	Over Voltage 2 Time Delay (0-16000 cyc)	6.00	0.00
	Frequency Monitor Settings		
27BLKP	Under Voltage Freq Block Threshold (50-100%)	70	70
81OU1P	Over Under Freq 1 (OFF, 40.1-69.9Hz)	57.0	57.5
81OU1D	Over Under Freq 1 Time Delay (0-16000 cyc)	6.00	5.00
81OU2P	Over Under Freq 2 (OFF, 40.1-69.9Hz)	59.3	58.5
81OU2D	Over Under Freq 2 Time Delay (0-16000 cyc)	116.00	120.00
81OU3P	Over Under Freq 3 (OFF, 40.1-69.9Hz)	60.5	60.5
81OU3D	Over Under Freq 3 Time Delay (0-16000 cyc)	6.00	120.00
81OU4P	Over Under Freq 4 (OFF, 40.1-69.9Hz)	OFF	61.5
81OU4D	Over Under Freq 4 Time Delay (0-16000 cyc)	6.00	5.00
	Directional Power Settings		
32P	Three Phase Power Threshold (OFF, 40-900W)	60	OFF
32FR	Forward or Reverse	R	n/a
32D	Time Delay (0-16000 cyc)	30.00	n/a
	Synchronism Check Settings		
25DIFP	Difference Voltage (OFF, 1-50%)	10	10
25SLP	Max Slip Freq (0.1-0.5HZ)	0.3	0.3
25ANG	Max Angle (2-60deg)	20	10

5.2 Control Equations

The protection functions described in Table 2, combined with relay logic inputs and outputs, are used by SELogic equations to realize numerous protection and control functions. In this application the equations are used to logically combine per-phase, over/under voltage and frequency functions, phase rotation functions, and alarm inputs to drive the grid interface contactor, as well as the Island Control and ESTOP inputs to the PCS(s). For details on the recommended control equations please reference Appendix A.

5.3 Resynchronization

As previously described, when a grid fault occurs the SEL-547 opens the grid interface contactor and asserts the discrete input to the PCS(s), which will seamlessly transition from grid-following to grid-forming mode. Once this transition occurs, the local micro-grid formed by the PCS is isolated from the faulted utility by the grid interface contactor.

At this point the SEL-547 continuously monitors the utility, waiting for it to return to within normal voltage and frequency operating ranges. Once the grid has been restored to acceptable conditions, the SEL-547 will wait until the utility and micro-grid comply with the IEEE-1547 synchronous interconnection criteria before closing the grid interface contactor and de-asserting the discrete input to the PCS. Those conditions, as defined by the “Synchronism Check Settings” in Table 2, are voltages within 10%, frequency within 0.3 Hz, and phase angle less than 20°. When the input is de-asserted, the PCS will seamlessly transition from grid-forming mode back to grid-following mode. Note that the time it takes for the phase angle to be less than the required 20° will depend on the difference between the utility and micro-grid frequencies.

6. PCS Register Changes

For seamless transfers to work correctly, all control decisions of when the grid is good or bad, and when the contactor should be opened or closed, must be driven by the SEL device. To ensure the SEL has control, the default grid monitor and ride through settings in the PCS need to be relaxed so it does not attempt to go OFFLINE or ONLINE on its own. When properly configured for seamless transfer, the PCS(s) should attempt to remain on-line and simply transition between grid-following and grid-forming modes as commanded by the SEL device.

To achieve this, the low and high voltage ride through curves must be disabled, and the default grid monitor thresholds widened to be outside of the SEL’s thresholds. Also, the SEL device requires the use of a neutral connection at the PCS, so the AC Connection Type configuration register needs to be set to 4-wire mode. These changes are summarized in the following table:

Register Number	Description	Units	Default Value	New Value
40272	LVRT Enable/Disable	n/a	1	0
40484	HVRT Enable/Disable	n/a	1	0
40696	LFRT Enable/Disable	n/a	1	0
40908	HFRT Enable/Disable	n/a	1	0
41169	Default Grid High Voltage Threshold	0.1 % Vref	1100	1150
41170	Default Grid Low Voltage Threshold	0.1 % Vref	880	500
41171	Default Grid High Frequency Threshold	0.01 Hz	6050	7000
41172	Default Grid Low Frequency Threshold	0.01 Hz	5850	5000
41240	AC Connection Type	n/a	0	1
42814	Grid Form Maximum Operating Voltage	0.1 % Vref	1100	1150
42815	Grid Form Minimum Operating Voltage	0.1 % Vref	700	500
42816	Grid Form Maximum Operating Frequency	0.01 Hz	6200	7000
42817	Grid Form Minimum Operating Frequency	0.01 Hz	5800	5000

Additionally, there are a handful of registers specific to enabling and controlling the timing of the seamless transfer operation. These are summarized in the following table and described in more detail below:

Register Number	Description	Units	Default Value	New Value
42813	Island Control Input Pin Configuration	n/a	0	4
42830	Island Control Input - Grid Tie to Island Debounce & Delay	ms	30	30
42831	Island Control Input - Island to Grid Tie Debounce & Delay	ms	40	40
42832	Seamless Transfer Offline Timeout Delay	ms	200	200
42833	Seamless Transfer to Island Voltage Ramp Up Delay	ms	20	20

Note that the opening and closing response time of the grid interface contactor will affect the grid-forming transition time independent of the PCS. Selecting a contactor with a rapid opening time is advised. In general AC actuated coils tend to operate faster than low-voltage DC coils.

6.1 Island Control Input Pin Configuration

This register must be set to a value of **4** to enable the Island Control pin to be used as an active low, seamless transfer control input. In this configuration, a logic low (or undriven) input will indicate that the PCS should operate in grid-forming mode, and a logic high value will indicate that the PCS should run in grid-following mode. This corresponds to the polarity of the SEL’s OUT2 logic configuration described above.

6.2 Island Control Input – Grid Tie to Island Debounce & Delay

This register is used to filter and delay the PCS response to a mode change request to transition from grid-following to grid-forming mode. In this case the goal is to have the PCS transition to grid-forming just prior to the grid contactor opening. As such, this time should be set to the minimum contactor open time to guarantee the PCS changes mode before the grid is disconnected.

6.3 Island Control Input – Island to Grid Tie Debounce & Delay

This register is used to filter and delay the PCS response to a mode change request to transition from grid-forming to grid-following mode. In this case the goal is to have the PCS remain in grid-forming mode until the grid contactor is guaranteed to be closed. As such, this time should be set to the maximum contactor close time.

6.4 Seamless Transfer Offline Timeout Delay

This register defines the OFFLINE timeout period during which the PCS will respond to a mode change request. It is used to handle the scenario in which the PCS transitions OFFLINE before the SEL device can change modes. In this case, the PCS will allow the requested mode change while OFFLINE, if the transfer command from the SEL device occurs within this timeout delay. If the SEL device fails to change modes within this delay period, the PCS will remain in the OFFLINE state and the system controller will have to manually start the micro-grid.

6.5 Seamless Transfer to Island Voltage Ramp Up Delay

This register is meant to account for the variation between min and max grid contactor open times. During the transition to grid-forming mode the PCS voltage output will remain at the sensed value at the time of the mode change until this delay expires. At that point, the PCS will begin slewing the voltage back to the nominal value. This register should be set to the difference between the contactor’s specified max open time to min open time.

7. Test Data

The following sections present actual test data demonstrating the seamless transfer performance of both single and paralleled OzPCS-RS40s. A Chroma 61860 grid simulator was used to create the various grid fault scenarios.

Unless otherwise specified, the scope channels shown below are as follows:

- CH 1 (Yellow) = A-to-B Grid Side Voltage (from Chroma)
- CH 2 (Blue) = A-to-B PCS Side Voltage
- CH 3 (Magenta) = Phase A Current from PCS
- CH 4 (Green) = SEL OUT2 Signal to PCS (Island Control Pin, high = Grid Tie, low = Island)

7.1 Single PCS Results

7.1.1 Slow Grid Faults

7.1.1.1 480 V_{RMS}/s Under Voltage, Pcmd=0kW, Load=20kW

The following plots illustrate a single PCS operating in grid-following mode when the grid voltage drops ~50%, from 480V_{RMS} to 242V_{RMS} at a rate of 480 V_{RMS}/s. In this case the PCS had been operating with a zero-power command prior to the event, so the PCS current is zero (magenta trace). When the gid voltage drops, the SEL device commands the PCS into grid-forming mode and opens the contactor (green trace going low). At this point the PCS restores the voltage (blue trace) and picks up the 20kW local load (magenta trace).

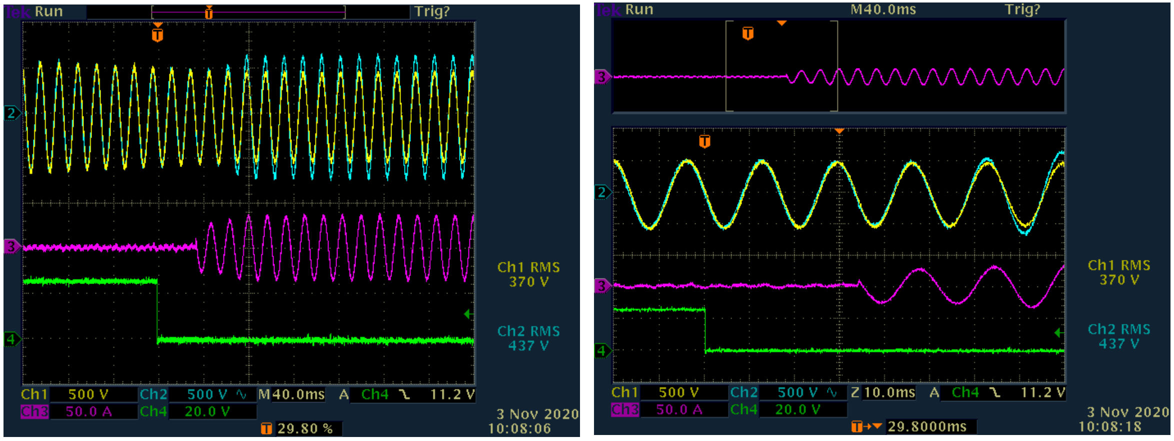

Figure 3 – Slow Under Voltage Ramp, Pcmd=0kW, Load=20kW

7.1.1.2 480 V_{RMS}/s Under Voltage, Pcmd=20kW, Load=20kW

This test case is the same as the previous except the PCS having been commanded 20kW in grid-following mode prior to the grid fault. The 20kW power command is evident in the PCS current output (magenta trace) prior to the fault. As the grid voltage drops, the PCS current increases to maintain the 20kW power command until the SEL device commands the PCS into grid-forming mode and opens the contactor (green trace going low). At this point the PCS restores the voltage (blue trace) and picks up the 20kW local load (magenta trace).

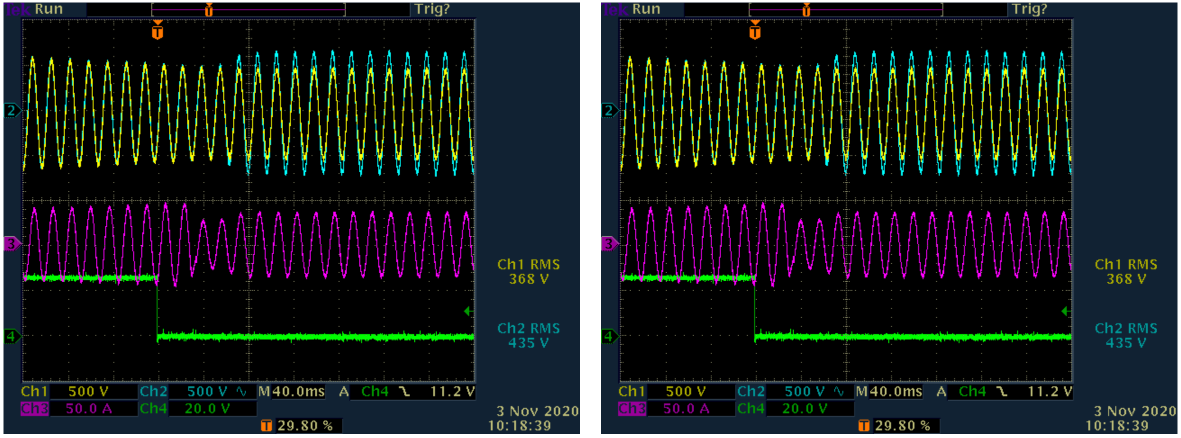

Figure 4 – Slow Under Voltage Ramp, Pcmd=20kW, Load=20kW

7.1.2 Fast Grid Faults

Figure 5 and Figure 6 illustrate the same test conditions as Figure 3 and Figure 4, except the grid voltage is stepped as fast as the grid simulator allows rather than slewing it at 480 V_{RMS}/s

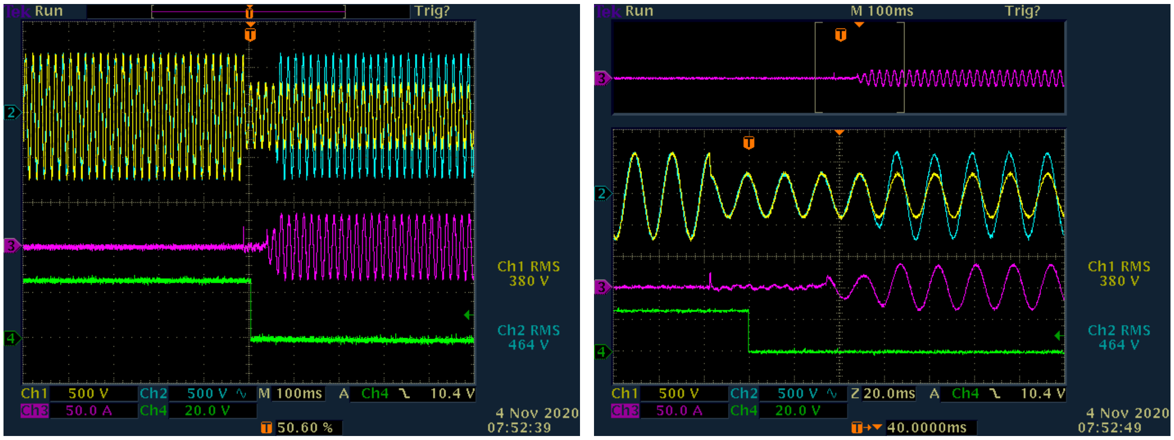

Figure 5 – Under Voltage Step, Pcmd=0kW, Load=20kW

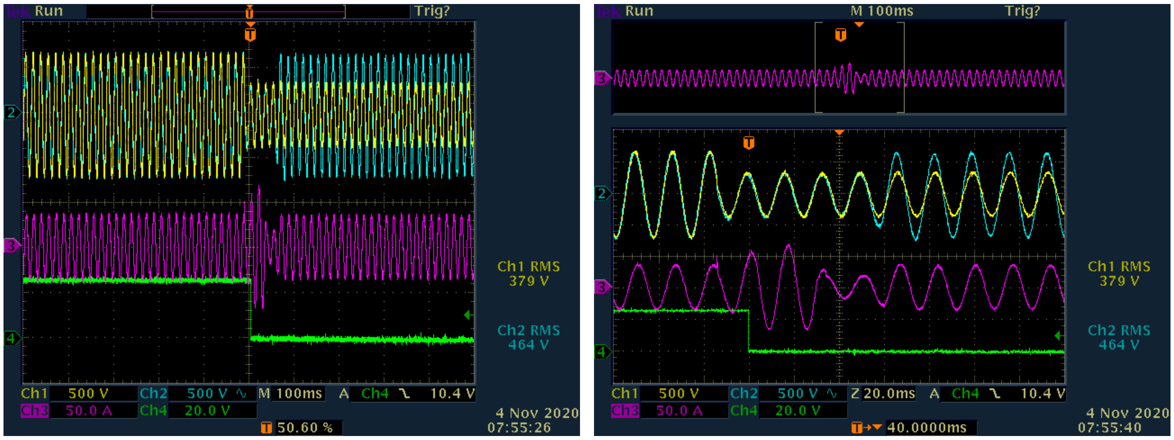

Figure 6 – Under Voltage Step, Pcmd=20kW, Load=20kW

7.2 Parallel PCS Results

To demonstrate the transition behavior of multiple PCS's, three PCS's were operated in parallel and the under-voltage test scenarios repeated. Note that in all plots, the three Power Conversion Systems simultaneously transfer modes and work together using droop control to restore and "form" the voltage (blue trace). The magenta trace is the output current from a single PCS and therefore represents one third of the total output/load current.

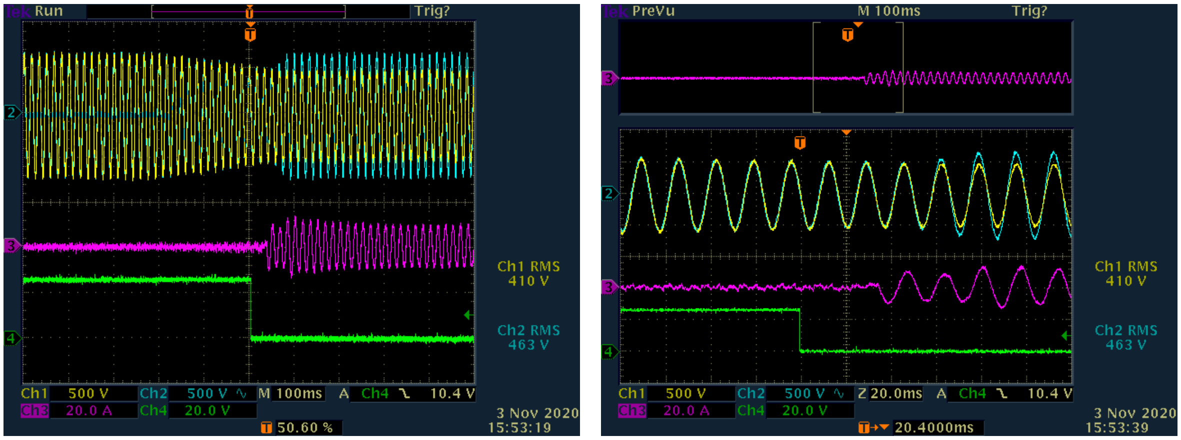

Figure 7 – Under Voltage Ramp, 3 Parallel PCS, Pcmd=0kW ea, Load=20kW

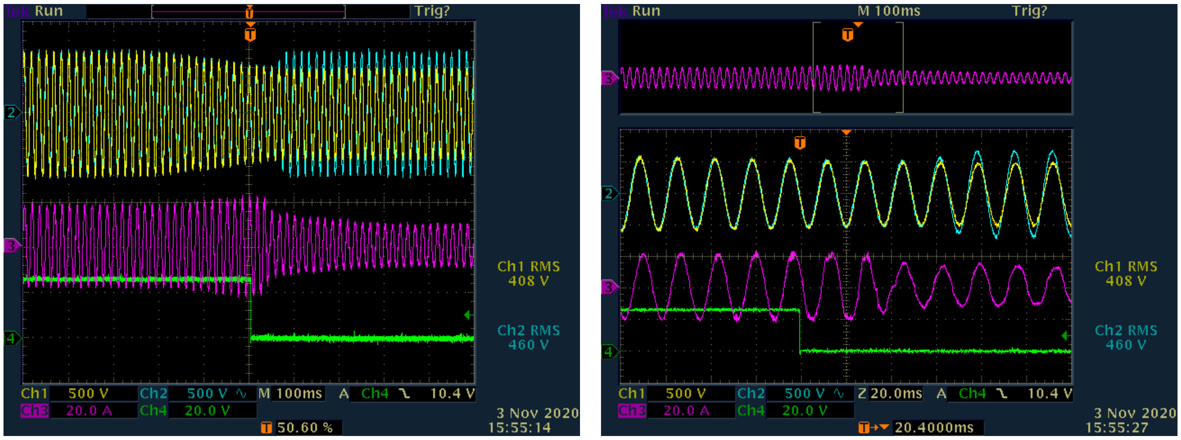

Figure 8 – Under Voltage Ramp, 3 Parallel PCS, Pcmd=10kW ea, Load=20kW

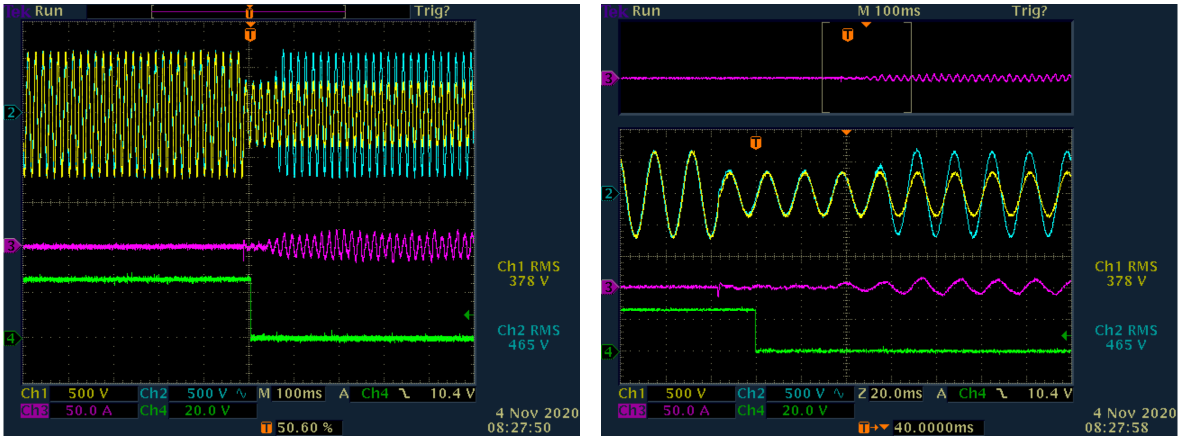

Figure 9 – Under Voltage Step, 3 Parallel PCS, Pcmd=0kW ea, Load=20kW

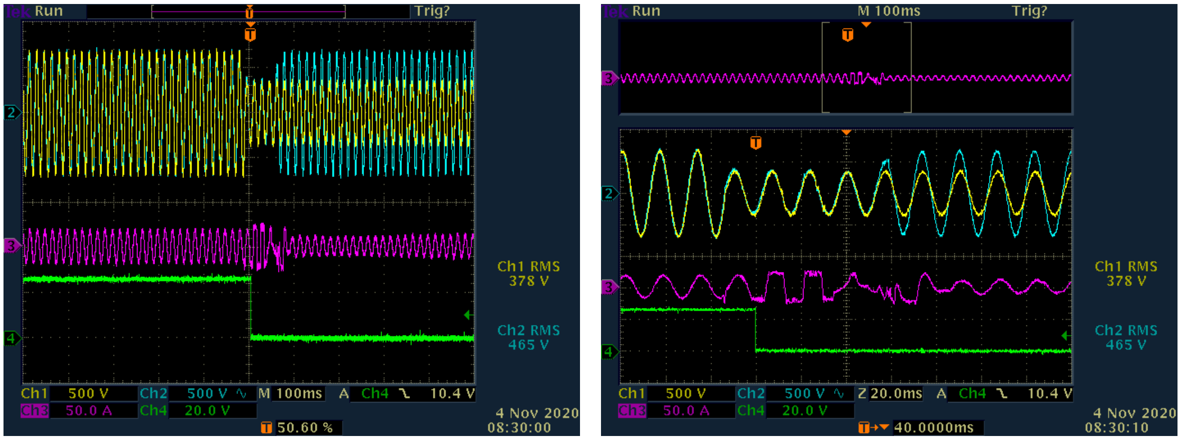

Figure 10 – Under Voltage Step, 3 Parallel PCS, Pcmd=10kW ea, Load=20kW

7.3 Resynchronization

Figure 11 illustrates three Power Conversion Systems seamlessly transitioning from grid-forming to grid-following mode. Prior to the SEL device closing the contactor (green trace going high), the three Power Conversion Systems are operating in grid-forming mode and supporting the 20kW load. Note that the magenta trace represents a single PCS current output of 1/3 the 20kW load current. Once the SEL-547 detects that the required resynchronization conditions described in section 5.3 have been met, it closes the grid interface contactor and signals the Power Conversion Systems to change to grid-following mode. Note that following the contactor closure, the Power Conversion Systems change modes and ramp the power back up to the previously commanded 10kW setpoint.

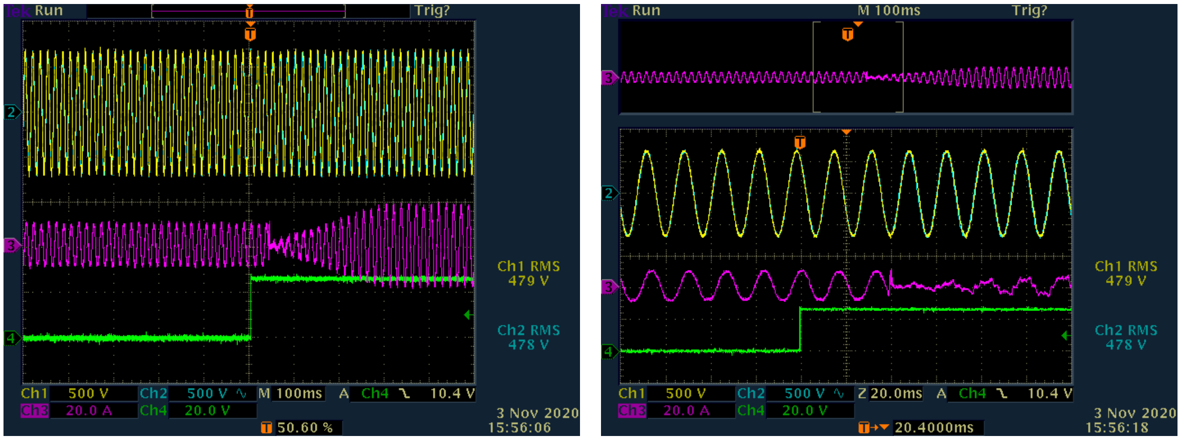

Figure 11 – Resynchronization, 3 Parallel PCS, Pcmd=10kW ea, Load=20kW

8. Appendix A

Table 3 shows the recommended SELogic variables and equations used to drive the grid interface contactor, as well as the Island Control and ESTOP inputs to the PCS(s). A brief description of each equation is provided in the bulletized list that follows.

Table 3 – SELogic Control Equations Summary

Variable	Control Equation
SV7	27A1 + 27B1 + 27C1
SV8	27A2 + 27B2 + 27C2
SV9	59A1 + 59B1 + 59C1
SV10	59A2 + 59B2 + 59C2
SV11	81D1T + 81D2T + 81D3T + 81D4T + ALARM
SV13	59Q1
SV14	25A1
SV15	!IN1 * OUT1 + IN1 * !OUT1
SV16	!(SV7T + SV8T + SV9T + SV10T + SV11T + SV13T)
OUT1	SV16T * (SV14T + OUT1)
OUT2	SV16T * (SV14T + OUT1)
OUT3	ALARM + SV15T
SS1	1
SS2	0
ER	\SV16T + /SV16T
BSYNCH	SV11T

- SV7 is used to detect under-voltage (level 1) on all three grid phases
- SV8 is used to detect under-voltage (level 2) on all three grid phases
- SV9 is used to detect over-voltage (level 1) on all three grid phases
- SV10 is used to detect over-voltage (level 2) on all three grid phases
- SV11 is used for over/under frequency detection as well as any ALARMs. In general, the ALARM is pulsed by the SEL device a) at power up, and b) any time the user changes to Password Level B or Level 2
- SV13 is used to detect the negative sequence voltage magnitude – this is used to enforce a particular phase rotation (ABC)
- SV14 is used to detect the synchronization check (whether both sides of contactor are within defined voltage/frequency/phase difference)
- SV15 is used to check for a grid connection contactor error by verifying that the contactor feedback (IN1) matches the contactor drive command (OUT1)
- SV16 combines all the “grid is good” checks (under-voltage, over-voltage, under/over-frequency, ALARM, and proper phase rotation).
- OUT1 is used to drive the contactor – which will be closed if “grid is good” and the synchronization check is valid. Note that the synchronization check is only used to

determine when to close the contactor. Once closed, we ignore the sync checking as it is susceptible to contactor bouncing and would otherwise cause the contactor drive to possibly chatter. Therefore, OUT1 is OR'ed with SV14T.

- OUT2 is used to drive the island control input pin to the Power Conversion Systems – this uses the identical equation as the OUT1 contactor drive output – i.e., the PCS sees the same signal as the contactor drive.
- OUT3 is used to drive the ESTOP input to the Power Conversion Systems – this is used to convey a contactor failure (feedback does not match drive) or an ALARM (someone has changed settings on the SEL device).
- OUT4 and OUT5 are not used, but they default to the SV16 “grid is good” logic.