Proper Single-Cell/Module Replacement and Bypass Procedures

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Abstract
Single-cell/module replacements (or bypasses) in series-connected strings can be tricky (a botched one, where only float current and not discharge current was taken into account, caused a famous fire that directly led to spill containment requirements). This is especially true when a single battery string is directly connected to a live load bus. This paper will explore the proper and safe methods of performing a single-cell change out in many different situations: online or offline, paralleled with the load or not, with immediate replacement or with temporary bypass and delayed replacement, with or without initial charge, etc.

Deleterious Effects of Improper Cell Replacement
In March of 1994, near the top floor of a large downtown telecommunications office in a major U.S. city, the end cells and end-cell switching system in an old telecommunications nominal -48 VDC plant were being replaced by single cells in each string to bring the plant up to modern 24-cell string standards. During the transition, relatively small cables were used to bypass the end cells so that the 24th cell could be added to each string. This worked fine while all that was flowing through the string was float current, but during the transition, Mr. Murphy caught the installers with their pants down, by failing the commercial AC. Of course, this failure caused a relatively high (but normal discharge) load to flow through the relatively small cables. This overheated the temporary (and undersized) cables that were running across several of the jars. Because the jars were not made of flame-retardant plastic, they caught fire and burned down to the electrolyte level. The fire also boiled some of the electrolyte so that it spilled over the burned recessed sides that remained on the jars.

When the fire department arrived, they sprayed water everywhere, thus spreading the electrolyte. The fire department was concerned about the exposure of their firemen to this electrolyte in future potential fires, and thus they helped push through the tentative interim amendment (TIA) to the Uniform Fire Code (UFC) in 1995 that required a 4” spill containment barrier 1” from each battery stand. This requirement was formally codified in the 1997 edition of the UFC. Since that time, spill containment requirements in the model codes (the IFC and NFPA 1 [the Fire Code]), and in the guidelines of IEEE 1578, have been changed to clarify that they don’t apply to VRLA batteries, and that there are other methods of spill containment besides the 4” barrier.

While there is value in permanently-installed spill containment for vented (flooded) batteries, there have been plenty of arguments in the meantime (and that are ongoing with certain AHJs) about when spill containment is required for existing installations, whether it is required for VRLA batteries, etc. Many of these arguments could possibly have been avoided if the cell replacements in the March 1994 fire had been properly planned and executed. This paper will give guidelines to proper cell replacement and bypass procedures for both single-string and multi-string DC buses.

Types of Cell/Module Replacements/Bypasses

There are several different types of battery cell/module replacements or bypasses. These are listed in the order of simplicity, and the order in which they will be covered in this paper:

- Off-line replacements where a pre-existing disconnect is used
- Off-line bypasses where a pre-existing disconnect is used
- Off-line replacements where the cables connecting to the DC bus do not have overcurrent protection and/or disconnects (sometimes referred to as "unfused")
- Off-line bypasses where the cables connecting to the DC bus don't have overcurrent protection and/or disconnects
- On-line replacements
- On-line bypasses

Off-Line Replacements with A Disconnect

Single cell or module replacements are simplest when the battery string (or a portion of the string) can be disconnected with a breaker (or disconnect switch) or connector (such as an Anderson SB®-type connector, or a pull-out fuse module). If the system is single-string, depending on the criticality of the load, an off-line, disconnected replacement may not be prudent (or it may not be possible for some types of charger(s)/rectifiers that cannot support the load without a battery acting as a filter). However, if it is a multiple string system, or the relatively low criticality of the load in a single string system with filtered charger(s)/rectifiers dictates that the load can be put at risk for a short period of time, follow these steps:

1. If the battery manufacturer recommends an initial/pre-charge, do so for the new module or cell at the manufacturer's recommended voltage for the recommended time period.
2. Disconnect the string or portion of the string by opening the breaker/switch or pulling the disconnect device.
3. Remove the intercell/module connectors of the cell or module that will be replaced.
4. Remove that cell or block from the stand/rack.
5. Place the new cell or module in the stand or rack.
6. Prior to terminating the intercell/module connector, use a voltmeter to measure for any potential difference between the new cell/module terminal post and the terminal post of the adjacent cell/module. For a safe termination there should be 0 V between them. If a potential difference exists, there may be a load or device (such as a high impedance permanent voltmeter) that is connected in parallel on the battery side of the disconnect that was not noticed. Always use the "dead – live – dead" practice of checking for any potential difference with a voltmeter. Reconnect the intercell/module connectors after proper cleaning, and application of a thin film of anti-oxidant. Use a calibrated torque wrench to tighten the bolts to the proper specifications per the battery manufacturer's instructions.
7. If the load is so sensitive that it requires voltage matching before re-connection, either lower the DC bus float voltage to match the voltage of the string/section that is to be reconnected as closely as possible, or put a charger on the string/section to bring it up to the bus voltage before re-closing the breaker/switch or plugging in the connector. If the load is not so sensitive, simply close the breaker/switch or reconnect the disconnect plug.

Off-Line Cell/Module Bypass with A Disconnect

In some cases, a replacement cell or module is not immediately available, but the existing cell or module is in such bad shape that it needs to be bypassed until it can be replaced. The bypass will reduce the reserve time (this will be covered later in this section), but the load won't be completely exposed to the whims of Mother Nature and/or the electric utility (which it could be with a bad cell or module, depending on the specific problem with that module).

A single-cell or module bypass is simplest when the battery string (or a portion of the string) can be disconnected with a breaker (or disconnect switch) or connector (such as an Anderson SB®-type connector, or a pull-out fuse module). As noted in the previous section, if the system has only a single string, depending on the criticality of the load, an off-line, disconnected bypass may not be prudent (or it may not be possible for some types of charger(s)/rectifiers that cannot support the load without a battery acting as a filter). However, if it is a multiple string system, or the relatively low criticality of the load in a single string system with filtered charger(s)/rectifiers dictates that the load can be put at risk for a short period of time, follow these steps:

1. **Consult Tables 1 and 2-5** (or calculate per NEC® rules) **for the proper cable size to use as a "bypass**", and prepare the proper length of cabling (typically, RHH/RHW DLO, or "welding" cable with Class K stranding, is used due to its flexibility, for ease of installation) with the proper connectors. For multi-cell modules with individual posts for each cell, the decision on whether to prepare enough cable length to bypass the whole module, or an individual cell, depends on whether the module will be replaced before the whole string is replaced; and if so, if the reduced reserve of a whole module bypass (see Table 6 for an estimate of reserve time reduction) is acceptable for the period of time before the new module is shipped and installed. Prepare the proper bolts (if you are going to re-use existing bolts, make sure they are properly cleaned of any corrosion after Step 3), and coat the lugs with a thin film of anti-oxidant. If the bypass cabling is going to run more than a couple of feet, and weighs more than a few pounds, it may be wise to plan a method of support for the bypass cabling that will prevent undue strain on the battery posts.
2. Disconnect the string or portion of the string by opening the breaker/switch or pulling the disconnect device. (Preferably the disconnect/breaker/switch removes both ends of the string or portion of the string from the bus so that it is floating with respect to ground and an accidental ground fault becomes much less likely.)
3. Remove the intercell/module connectors of the cell or module that will be bypassed. **NEVER bypass the cell or module by connecting the bypass cabling first**.
4. Connect the bypass cabling, and use a calibrated torque wrench to tighten the bolts to the battery manufacturer's recommended value. Prior to terminating the intercell/module connector, use a voltmeter to measure for potential difference between the new cell/module terminal post and the terminal post of the adjacent cell/module. If a potential difference exists, there may be an unnoticed load or device (such as a high impedance permanent voltmeter) that is connected in parallel on the battery side of the disconnect. For grounded battery systems (such as telecommunications), caution needs to be exercised to ensure that the bypass cable does not accidentally make contact to ground during the terminations. To reduce this risk, the first termination should be made to the terminal post of the cell/module on the "hottest" side of the cell/module that is being bypassed. This is the side closest to the disconnect. For example, in a -48 V system (where the positive side is grounded), the positive post of the cell upstream (towards the negative end of the string) next to the cell/module being bypassed should get the first connection. Then, the final termination can be made to the negative terminal of the post on the downstream side (toward the grounded end of the string). Prior to making that final termination, verify with a voltmeter that there is 0 potential difference between the bypass cable and the cell/module terminal post on the downstream side (towards the grounded end).
5. If an entire module was bypassed, or if a stand-alone cell was bypassed, it may be removed from the rack/stand, or this step can wait if the replacement cell/module will be coming in the next several months (in a seismically-qualified configuration, it needs to stay in place to maintain the seismic rating).

6. Look at the battery manufacturer's recommended float voltage range per cell, multiply it by the remaining cells in the string, and if this is a single string plant, set the DC bus to this level. If this is a multiple string system, it is not so simple. For vented systems where up to 5% of the cells were bypassed, the float voltage can be maintained at the existing level (although it can be turned down a little towards the top-end of the recommended float range for the string with the fewest number of cells) for several months until the replacement cell arrives. Maintaining the existing float will slightly shorten the life of the existing cells in the string with the bypass, and increase the watering, but will maintain the longest possible reserve time for the system. For VRLAs (especially "starved-electrolyte" AGMs), maintaining a higher float voltage increases the risk of thermal runaway and significantly shortens life. In these cases, the float voltage should generally be set no higher than the highest recommended float voltage per cell multiplied by the number of remaining cells in the string that has bypassed cells (this means that in a bypass situation for VRLA cells, the float voltage almost always needs to be lowered). This will further reduce capacity, but is necessary for safety reasons. Examples will be given later in this section to help with the proper float setting.
7. If the load is so sensitive that it requires voltage matching before re-connection, either lower the DC bus float voltage to match the voltage of the string/section that is going to be reconnected as closely as possible, or put a charger on the string/section to bring it up to the bus voltage before re-closing the breaker/switch or plugging in the connector. After reconnection, return the float voltage to the level determined in Step 6. If the load is not so sensitive, simply close the breaker/switch or reconnect the disconnect plug.

As noted earlier, undersizing bypass cabling can have serious consequences. The user must determine the maximum current that will normally be carried (except for fault situations) in a charge or discharge situation, then match it with the appropriate cable, ensuring that the cable is rated for an ampacity equal to or greater than the disconnect's standard rating where a disconnect is employed (NEC® Article 240.4B allows a cable ampacity just below a breaker value for breakers rated 800 A or smaller; but in this author's opinion, that exception should rarely, if ever, be employed). In this case, because the bypass cable(s) are typically single cables in free air, the 75°C ampacity column of Table 310.15(B)(17) of the NEC® should usually be used (while the conductor itself is sometimes rated for 90 or even 105°C, the connection points are rarely Listed above 75°C, therefore, per NEC® Article 110.14C, the 75°C column should be used). Further ampacity deratings, as required by the Code for specialized circumstances (such as a higher temperature operating environment) may also be required. In Table 1, the 75°C column for the most common copper conductor sizes from the 2011 NEC Table 310.15(B)(17) is reproduced.

Table 1 - Free-Air Single-Conductor Ampacities of Common Copper Bypass Cables

Table 1, Free-Air Single-Conductor Ampacities of Common Copper Bypass Cables	
Cable Size	**Ampacity**
14 AWG	15
12 AWG	20
10 AWG	30
8 AWG	70
6 AWG	95
4 AWG	125
3 AWG	145
2 AWG	170
1 AWG	195
1/0 AWG	230
2/0 AWG	265
3/0 AWG	310
4/0 AWG	360
262.6 kcmil	405
313.1 kcmil	445
350 kcmil	505
373.7 kcmil	
444.4 kcmil	545
500 kcmil	620
535.3 kcmil	
646.4 kcmil	690
750 kcmil	785
777.7 kcmil	
929.2 kcmil	870
1111.1 kcmil	935

Typical average discharge current ratings for the most common lead-acid battery types at common rates are given in Tables 2-5 for protector and cable sizing purposes (much more accurate rates are available from manufacturer sizing programs and tables for the exact model number):

Table 2 - Typical Vented Utility and Telecom Lead-Acid Battery Rates to Typical End-of-Discharge Voltage

Table 2, Typical Vented Utility and Telecom Lead-Acid Battery Rates to Typical End-of-Discharge Voltage				
Ah rating	**1 min rate**	**3 h rate**	**4 h rate**	**8 h rate**
200	265	46	35	22
360	448	85	60	39
450	582	107	75	48
540	732	129	91	58
660	871	157	110	71
720	526	171	121	77
840	1048	199	140	91
1176	1153	258	199	126
1344	1431	330	227	144

Table 2, Typical Vented Utility and Telecom Lead-Acid Battery Rates to Typical End-of-Discharge Voltage				
Ah rating	**1 min rate**	**3 h rate**	**4 h rate**	**8 h rate**
1680	1700	369	280	181
1810	1806	398	306	194
2110	2054	459	366	223
2320	2235	505	409	243
3623	3067	693	600	384
4000	3385	765	653	418

In Tables 2 and 3, a typical end-of-discharge voltage of 1.75 V per lead-acid cell (at 25°C) is used for the typical utility sizing rates of 1 minute and 3 hours; while a typical end-of-discharge voltage of 1.86 V/cell is used for the telecommunications 4 and 8-hour sizing paradigms.

Table 3 - Typical Utility and Telecom VRLA Battery Rates to Typical End-of-Discharge Voltage

Table 3, Typical Utility and Telecom VRLA Battery Rates to Typical End-of-Discharge Voltage				
Ah rating	**1 min rate**	**3 h rate**	**4 h rate**	**8 h rate**
7	45	1.9	1.5	0.8
12	76	3.3	2.5	1.3
18	101	5.0	3.5	1.9
30	179	8.3	6.5	3.5
60	262	16	14	7.5
70	310	18	15	8.0
80	330	20	16	9.1
90	360	23	19	10
100	400	27	21	11
125	500	32	26	15
145	507	37	29	17
170	514	47	35	20
190	518	55	40	23
570	607	133	110	60
760	860	179	140	86
1045	1161	247	201	119
1520	1693	358	293	173
2000	2211	472	371	227
3000	3321	709	556	340

Note that more than one cable can be used to meet ampacity requirements for a bypass cable set (for example, some battery posts are built for 4 straps, so up to 4 cables could be used per post in that case; and/or some cells have multiple posts).

In Tables 4 and 5, the rates are typical for a UPS end voltage of 1.67 V/cell at 25°C:

Table 4 - Typical Vented UPS Battery Ampere Rates to Typical End-of-Discharge Voltage

Table 4, Typical Vented UPS Battery Ampere Rates to Typical End-of-Discharge Voltage				
W/cell rating	**5 min rate**	**15 min rate**	**30 min rate**	**45 min rate**
1000	919 A	619 A	421 A	325 A
2000	1501 A	1184 A	887 A	685 A
3000	2372 A	1792 A	1225 A	946 A
4200	3575 A	2492 A	1719 A	1328 A
4900	4246 A	2945 A	2013 A	1543 A
5800	4363 A	3489 A	2633 A	2033 A
7500	5634 A	4505 A	3399 A	2624 A

Table 5 - Typical VRLA UPS Maximum Battery Ampere Rates at Typical End-of-Discharge Voltage

Table 5, Typical VRLA UPS Maximum Battery Ampere Rates at Typical End-of-Discharge Voltage				
W/cell rating	**5 min rate**	**15 min rate**	**30 min rate**	**45 min rate**
25	27 A	14 A	7.8 A	6.0 A
35	43 A	22 A	12 A	9.0 A
50	66 A	32 A	19 A	14 A
100	118 A	60 A	34 A	25 A
135	159 A	81 A	46 A	34 A
150	177 A	90 A	51 A	37 A
200	245 A	123 A	71 A	53 A
300	337 A	170 A	106 A	77 A
350	381 A	201 A	123 A	90 A
400	433 A	229 A	139 A	101 A
500	523 A	304 A	181 A	139 A
550	557 A	324 A	196 A	141 A
625	562 A	371 A	246 A	173 A
700	634 A	417 A	259 A	193 A
750	657 A	449 A	299 A	214 A
800	713 A	467 A	308 A	219 A
925	784 A	554 A	341 A	250 A
1100	810 A	664 A	525 A	426 A
2000	1484 A	1217 A	963 A	780 A
3000	2159 A	1770 A	1401 A	1181 A
3400	2508 A	2056 A	1658 A	1353 A
4100	3006 A	2455 A	1923 A	1570 A

The tables (those above or those of the battery manufacturer) can be used for simplicity if the designed reserve times are known. However, the actual loads are almost always lower than the future loads and derating factors used to design battery backup, and if a large enough cable is not readily available, calculations can be done to determine if the available cable is sufficient to carry the loads safely. In addition, excess charger capacity can actually increase the size of bypass cable needed because the batteries will accept almost all current available to them when they are discharged.

Per Chapter 2 of the Code, the ampacity of protectors and cables should be sized at a minimum of 125% of the continuous load + 100% of the non-continuous load.

As an example, in a utility application with a single string, the actual constant current load on battery discharge might be 134 A, while the motor start-up currents are 335 A. After applying a derating factor to account for normal aging, plus a load growth design margin factor, the battery chosen to meet the desired 3 h reserve time, while still being able to meet the motor start-up currents, ends up being a nominal 874 Ah vented lead-acid battery. The charger is rated at 200 A and current-limited to 105%), and the float current is less than 1 Amp. Table 2 would suggest a disconnect size of 1,200 A (see NEC® 240.6A) based on the approximate 1-minute rate of a nominal 874 Ah vented lead-acid battery. This could drive the use of two 535.3 kcmil cables (see Table 1) for the bypass set to meet the ampacity of the disconnect. However, running our own calculations, based on the real loads, yields:

$$I_{dischg-calc} = (134\ A\ \times 125\%) + (335\ A\ \times 100\%) \approx\ 503\ A$$

$$I_{rechg-calc} = (1\ A\ \times 125\%) +\ \Big(\big((200\ A \times 105\%) - 1\ A\big) \times 100\%\Big) \approx 210\ A$$

Of these two calculations, the discharge is the worst case, and this means that a 600 A disconnect can be used for the string, and a single 535.5 kcmil cable can be used for the bypass.
In a UPS or telecom application, the continuous discharge load is typically considered to be the load at nominal voltage during discharge, while the additional load due to constant-power discharge at the end-of-discharge voltage is considered to be the non-continuous discharge load. In a recharge situation, the continuous load is the float current, and the non-continuous load is the amount of current the charging system could produce minus any parallel loads and minus the float current (because the float current is already accounted for in the calculation).

As an example, in a particular telecom application, the float constant-power load of a nominal -48 V system at -52.80 V is 112 A, and the battery backup is designed for a minimum of 4 hours with an end voltage at the plant of -44.64 (1.86 V/cell). After applying end-of-life derating factors and a load-growth design margin, as well as choosing a common battery size, the battery reserve is designed with a single string of vented lead-calcium 1680 Ah batteries, which has a float current of less than 2 A. There are eight 50 A rectifiers (current-limited to 110%) in parallel to serve both the load and the batteries. Per Table 2, this would require a bypass cable with at least 280 A of ampacity. From Table 1, a 3/0 AWG will meet the need.

However, our own calculations may yield a smaller (or larger due to the excess rectification) minimum cable size for the bypass cable. The constant-power float load can be simply converted into Watts:

$$P_{DC} =\ I_{DC} \times V_{DC} = 112 \times\ 52.8 = 5914\ W$$

The average continuous discharge load can then be computed using the same formula, algebraically manipulated:

$$I_{avg} = \frac{P_{DC}}{V_{nom}} = \frac{5914}{48} \approx 123\ A$$

The peak current can be similarly computed:

$$I_{pk} = \frac{5914}{44.64} \approx 132\ A$$

The NEC® formula can then be used for computing the minimum bypass cable ampacity:

$$I_{dischg-calc} = (123 \times 125\%) + ((132 - 123) \times 100\%) \approx 163\ A$$

$$I_{rechg-calc} = (2 \times 125\%) + ((8 \times 50 \times 110\%) - 112 - 2) \times 100\%) \approx 329\ A$$

In this case, the recharge calculation yields the worst-case current (even worse than the 280 A from Table 2). Per Table 1, this means that a 4/0 AWG cable should be used for the bypass cabling.

Finally, a UPS example illustrates the same point. In this example, an 80 kVA UPS (actual load is 19.2 kW) with an assumed power factor of 80% is designed for a 15-minute battery backup. The system float voltage is around 540 V for connection of one or more strings of 240 cells of VRLA or high-gravity vented batteries. The inverter cutoff voltage is 400 V (1.67 V/cell), and the inverter conversion efficiency is a relatively-constant 96%. The charger DC bus output in the UPS feeds both the batteries and inverter input in parallel, and is rated at 200 A (and current-limited at that value as well). Using an age-derating factor, the UPS manufacturer recommends a single string of 400 W/cell 12 V VRLA monobloc batteries in a cabinet with a 300 A disconnect breaker (see Table 5). The DC float current of these batteries is less than 1 A, and the AC ripple current through the batteries is typically about 5 A. The intercell connectors provided for the top-terminal batteries are 3/0 AWG (see Table 1).

Running the calculations to determine if a smaller bypass cable could be used (or if a larger one is needed) yields the following results:

$$P_{DC-dischg} = \frac{19200\ W}{0.96} = 20000\ W$$

$$I_{avg-dischg-DC} = \frac{20000\ W}{480\ V} \approx 42\ A$$

$$I_{pk-dischg-DC} = \frac{20000\ W}{400\ V} = 50\ A$$

$$I_{dischg-calc-DC} = (42 \times 125\%) + (50 - 42) \approx 60\ A$$

$$I_{load-DC@flt} = \frac{20000\ W}{540\ V} \approx 37\ A$$

$$I_{rechg-calc-DC} = \big((1 + 5) \times 125\%\big) + \big((200 - 37 - 1) \times 100\%\big) \approx 170\ A$$

In this case, the maximum recharge current calculation is going to determine the bypass cable size, and per Table 1, that would require a 2 AWG bypass cable. While that does not cover the ampacity of the 300 A disconnect, it should be fine as a temporary solution until a new monobloc arrives for the replacement.

As mentioned in Step 1 of the bypass procedure of this section, bypassing a cell or cells will reduce the capacity that remains in that string. Table 6 estimates average reductions in backup capacity for common nominal DC plant voltages, reserve times, and end voltages. If no value is given in the cell, it typically means that many cells should not be bypassed for that nominal voltage and backup time configuration because the coup de fouet could cause an almost immediate dip below the minimum voltage required by the load, especially for the long-duration batteries; or it could mean that data was not available from the manufacturers to compute the capacity reduction.

Table 6 - Typical Single String Capacity Reductions Based on Temporary Cell Bypasses

Table 6, Typical Single String Capacity Reductions Based on Temporary Cell Bypasses										
nominal DC Bus Voltage	Reserve Time	# of Cells Bypassed								
		1	2	3	4	6	12	18	24	30
24	4 h									
	8 h	79%								
48	4 h	39%								
	8 h	33%	79%							
125	3 h	6%	12%	23%	44%					
250	3 h	3%	6%	9%	12%	23%				
360	15 min	1%	3%	5%	7%	12%	31%	54%	78%	99%
	5 min	2%	5%	8%	10%	16%	49%			
480	15 min	1%	3%	4%	6%	8%	20%	35%	56%	83%
	5 min	2%	4%	7%	8%	12%	30%	52%	80%	

The reductions in Table 6 are based on starting with (before bypass) typical 12 and 24-cell lead-acid end voltages of 1.86 V/cell for telecom 4 and 8-hour rates, 1.75 V/cell in 60 and 120-cell strings for utility 3-hour rates, and 1.67 V/cell in 180 and 240-cell strings for the typical UPS 5 and 15 minute rates. These reductions are very dependent on individual battery models and manufacturers; thus the table simply gives a general idea of reduction percentages that could possibly be seen.

As noted in step 6 of the procedure of this section, examples for resetting the float voltage after a bypass are useful.

The first example is of a nominal 125 V utility DC plant that originally had 60 vented cells in series, but now has the need to bypass 2 cells. This particular battery's recommended float range for the 1.215 s.g. lead-calcium cells is 2.20-2.26 V/cell, and they were originally floated at 2.25 V/cell (an overall plant float of 135 V). If the float voltage is kept the same, the new float would be about 2.33 V/cell for that string. In order to reduce watering and premature aging, assuming parallel 60-cell strings, the float voltage could be turned down to the manufacturer's lowest recommended level (2.20 V/cell = 132 V plant float), which impresses an average of about 2.27 V across the remaining cells. While this is still outside the recommended range, assuming the cells will be replaced within a few months, very little long-term damage will be done to the vented batteries.

In a 24 V telecom plant, the 1.215 s.g. vented cells are typically floated at 2.20 V/cell (26.4 V plant float). The need to bypass one bad cell results in an average of 2.4 V/cell impressed across the remaining 11. Telecom plants often have parallel strings, and the float can be lowered to 2.17 V/cell average (26.04 V plant float) for a short period of time across the parallel strings until the replacement cell is installed. This results in an average of 2.37 V/cell in the string with the bypassed cell.

In a nominal -48 VDC telecommunications plant using large 2 V VRLA AGM batteries, the recommended float range from this particular battery manufacturer is 2.25-2.28 V/cell, and the float voltage of the plant is set at -54.25 V. A bypassed single cell in string A, and a plant float voltage lowered to -54.0 V to accommodate the 24 cells each in strings B, C, and D results in an average of 2.35 V/cell across the 23 remaining cells in string A. This is unacceptable for months, as the battery manufacturer does not allow this boost-charge level for starved-electrolyte cells to exceed 48 hours, and the replacement cell will not arrive for another 6 weeks. The compromise is to lower the float voltage to -52.44 (2.28 V/cell for the 23-cell string, and 2.185 V/cell for the remaining 24-cell strings), along with a weekly 24-hr equalize boost charge at -54.0 V to recover string capacity for any discharges that Mother Nature might throw at the user.

Finally, in a UPS application using forty 12 V VRLA monoblocs floated at 545 V (2.27 V/cell average), a single bad monobloc must be bypassed. This particular manufacturer has a recommended float voltage range of 13.38-13.62 V/monobloc (2.23-2.27 V/cell). Lowering the DC bus float voltage to the lower end of the manufacturer's specified range for the parallel strings results in a new float voltage of 535.2 (for the string with the bypassed module, this is 13.72 average across each monobloc, and 2.29 average across each cell). While this is a little above the manufacturer's recommended range, this is probably acceptable for a few weeks or months until the replacement cell arrives, especially if temperature compensation is employed to mitigate the increased risk of thermal runaway due to the higher float voltage.

Off-Line Replacement of a Cell/Module That Was Bypassed

When the replacement cells arrive, the proper steps must be followed to remove the bypass and insert the replace cell/module. These are similar to the same steps given earlier in this section, except somewhat in reverse.

1. Pre-charge the new cell(s)/module(s) if required, per manufacturer instructions.
2. Disconnect the string or portion of the string by opening the breaker/switch or pulling the disconnect device.
3. Remove the bypass cable(s).
4. If the original cell or module that was bypassed was not removed from the rack/stand, do so now.
5. Put the new cell in position on the rack/stand.
6. If the old intercell/module connectors are going to be re-used, clean them properly as needed, and re-apply a thin film of anti-oxidant. If new intercell/module connectors are going to be used, prepare them in a similar manner.
7. Connect the intercell/module connectors, and use a calibrated torque wrench to tighten the bolts to the battery manufacturer's recommended value. Prior to terminating the intercell/module connector, use a voltmeter to measure for potential difference between the new cell/module terminal post and the terminal post of the adjacent cell/module. If a potential difference exists, there may be a load or other unnoticed device that is connected in parallel on the battery side of the disconnect.
8. If the float voltage had been adjusted down to account for the bypassed cell(s), readjust it to its original setting.
9. If the load is so sensitive that it requires voltage matching before re-connection, either lower the DC bus float voltage to match the voltage of the string/section that is going to be reconnected as closely as possible, or put a charger on the string/section to bring it up to the bus voltage before re-closing the breaker/switch or plugging in the connector. After reconnection, return the float voltage to the final level of Step 8. If the load is not so sensitive, simply close the breaker/switch or reconnect the disconnect plug.

Off-Line Replacements Where the DC Bus Connection Does Not Have a Disconnect

For reliability reasons (to avoid an extra potential point of failure), some telecommunications DC plants (and some other industries as well) do not use a disconnect between the DC bus and the battery string(s). While this improves reliability, it complicates making single cell/module replacements. In summary, reconnection almost always requires voltage matching, and the disconnected cables must be protected from accidental grounding. Here are the steps to follow

1. If the battery manufacturer recommends an initial/pre-charge, do so for the module or cell at the manufacturer's recommended voltage for the recommended time period.
2. Disconnect the string by removing the cabling that ties it to the DC buses (both the hot and return sides). As this is done, special care must be taken to ensure that the newly freed cable(s) do not contact any grounded object or any other battery post (use of insulated tools, and insulating blankets or materials on nearby cells and metal without compromising the venting ability of nearby cells is particularly helpful in avoiding accidents). This is typically done with electrical tape or heat-shrink boots.
3. Remove the intercell/module connectors of the cell or module that will be replaced.
4. Remove that cell or block from the stand/rack.
5. Place the new cell or module in the stand or rack.
6. Reconnect the intercell/module connectors after proper cleaning, and application of a thin film of anti-oxidant. Use a calibrated torque wrench to tighten the bolts to the proper specifications per the battery manufacturer's instructions. Prior to terminating the intercell/module connector, use a voltmeter to measure for potential difference between the new cell/module terminal post and the terminal post of the adjacent cell/module. If a potential difference exists, there may be a load or other unnoticed device that is connected in parallel on the battery side of the disconnect.
7. Either lower the DC bus float voltage to match the voltage of the string that is to be reconnected as closely as possible, or put a charger on the string to bring it up to the bus voltage before removing the electrical tape or heat shrink from the cables at the "hot" end of the string and reconnecting them (use a voltmeter to verify minimal potential difference prior to connection).

Off-Line Bypasses Where the DC Bus Connection Does Not Have OverCurrent Protection and/or a Disconnect Device

Here are the steps to bypass a bad cell/module off-line when there is no disconnect:

1. Consult Tables 1 and 2-5 (or calculate per NEC® rules) for the proper cable size to use as a "bypass", and prepare the proper length of cabling with the proper connectors. Prepare the proper bolts, and coat the lugs with a thin film of anti-oxidant. If the bypass cabling is going to run more than a couple of feet, and is of a larger size, it may be wise to plan a method of support for the bypass cabling that will prevent undue strain on the battery posts.
2. Disconnect the string by removing the cabling that ties it to the DC bus (this is typically only done on the "hot" side). As this is done, special care must be taken to ensure that the newly freed cable(s) do not contact any grounded object or any other battery post. This is typically done with electrical tape or heat-shrink boots.
3. Remove the intercell/module connectors of the cell or module that will be bypassed. **NEVER bypass the cell or module by connecting the bypass cabling first**.
4. Connect the bypass cabling, and use a torque wrench to tighten the bolts to the recommended value. Prior to terminating the intercell/module connector, use a voltmeter to measure for potential difference between the new cell/module terminal post and the terminal post of the adjacent cell/module. If a potential difference exists, there may be a load or other unnoticed device that is connected in parallel on the battery side of the disconnect.
5. If an entire module was bypassed, or if a stand-alone cell was bypassed, it may be removed from the rack/stand, or this step can wait if the replacement cell/module will be coming in the next several months (in a seismically-qualified configuration, it needs to stay in place to maintain the seismic rating).

6. Look at the battery manufacturer's recommended float voltage range per cell, multiply it by the number of cells remaining in the string, and if this is a single string configuration, set the DC bus to this level. If it is a multiple string system, it is not as simple. For vented systems where up to 5% of the cells were bypassed, the float voltage can probably be maintained at the existing level (although it can also be turned down a little towards the top-end of the recommended float range for the string with the fewest cells) for several months until the replacement arrives. Maintaining this existing float level will slightly shorten the life of the existing cells in the string with the bypass, and increase its watering interval, but it will maintain the longest possible reserve time of the overall system. For VRLA cells (especially those of the "starved-electrolyte" AGM type), maintaining a higher float voltage increases the risk of thermal runaway and significantly shortens life. In these cases, the float voltage should generally be set no higher than the highest recommended float voltage per cell multiplied by the number of remaining cells in the string that has bypassed cells (in other words, for VRLA battery plants where cells are bypassed, the float voltage almost always needs to be turned down). This will further reduce capacity, but is necessary for safety reasons. Some examples were given previously in this document to help with proper setting of the new float.
7. Either lower the DC bus float voltage to match the voltage of the string that is to be reconnected as closely as possible, or put a charger on the string to bring it up to the bus voltage before removing the electrical tape or heat shrink from the cables at the "hot" end of the string and reconnecting them (use a voltmeter to verify minimal potential difference prior to connection).

When the replacement cell/module arrives, follow these steps.

1. Pre-charge the new cell(s)/module(s) if required, per manufacturer instructions.
2. Disconnect the string by removing the cabling that ties it to the DC bus (this is typically only done on the "hot" side). As this is done, special care must be taken to ensure that the newly freed cable(s) do not contact any grounded object or any other battery post. This is typically done with electrical tape or heat-shrink boots.
3. Remove the bypass cable(s).
4. If the original cell or module that was bypassed was not removed from the rack/stand, do so now.
5. Put the new cell in position on the rack/stand.
6. If the old intercell/module connectors are going to be re-used, clean them properly as needed, and re-apply a thin film of anti-oxidant. If new intercell/module connectors are going to be used, prepare them in a similar manner.
7. Connect the intercell/module connectors, and use a calibrated torque wrench to tighten the bolts to the battery manufacturer's recommended value. Prior to terminating the intercell/module connector, use a voltmeter to measure for potential difference between the new cell/module terminal post and the terminal post of the adjacent cell/module. If a potential difference exists, there may be a load or other unnoticed device that is connected in parallel on the battery side of the disconnect.
8. If the float voltage had been adjusted down to account for the bypassed cell(s), readjust it to its original setting.
9. Either lower the DC bus float voltage to match the voltage of the string/section that is going to be reconnected as closely as possible, or put a charger on the string/section to bring it up to the bus voltage before removing the electrical tape or insulating boots from the connecting cabling, and reconnecting the string (use a voltmeter to verify minimal potential difference prior to connection). After reconnection, return the float voltage to the final level of Step 8.

On-Line Replacements

When the replacement must be done on-line either to maintain backup capacity, or because it is a single-string configuration that can't lose the battery's filtering capability, further complications ensue. The steps are as follows:

1. If the battery manufacturer recommends an initial/pre-charge, do so for the new module or cell at the manufacturer's recommended voltage for the recommended time period.
2. Find temporary cabling and connectors capable of handling the discharge current per Tables 1 and 2-5 (or calculate per NEC® rules), and prepare it. The cabling must be flexible, and long enough to allow for movement.
3. Set up the new cell on a hoist, or on the floor and connect it up as shown in Figure 1
4. Remove the intercell/module connectors of the cell or module that will be replaced (see Figure 2).
5. Remove that cell or block from the stand/rack and place it on the ground or on a second hoist (see Figure 3).
6. Place the new cell or module in the stand or rack while maintaining the flexible cabling (see Figure 4).
7. Reconnect the intercell/module connectors after proper cleaning, and application of a thin film of anti-oxidant. Use a calibrated torque wrench to tighten the bolts to the proper specs per the manufacturer's instructions. (See Figure 5.)
8. Remove the temporary cabling (see Figure 6).

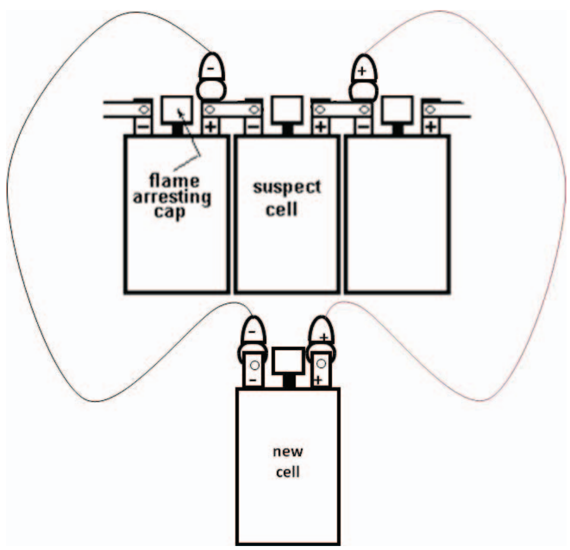

Figure 1 - Temporary Cabling for an On-Line Single-Cell/Module Replacement

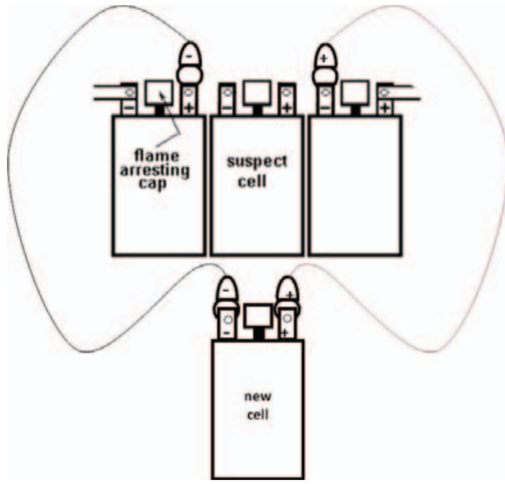

Figure 2 - Removing the Intercell Connectors During an On-Line Single-Cell/Module Replacement

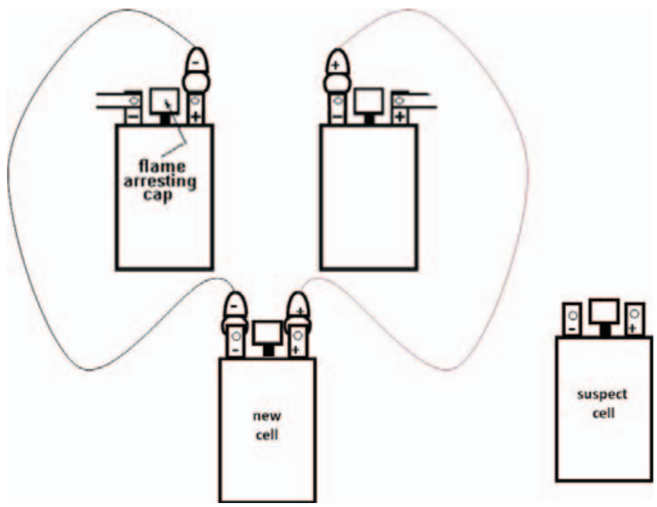

Figure 3 - Removing the Suspect Cell During an On-Line Single-Cell/Module Replacement

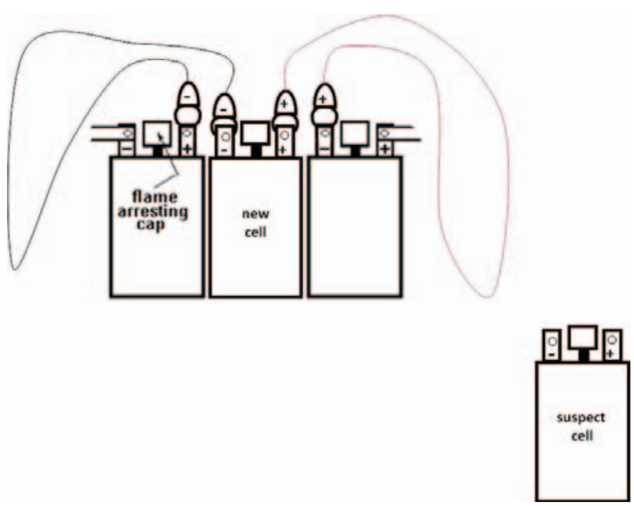

Figure 4 - Putting the Replacement Cell/Module in the Rack During an On-Line Replacement

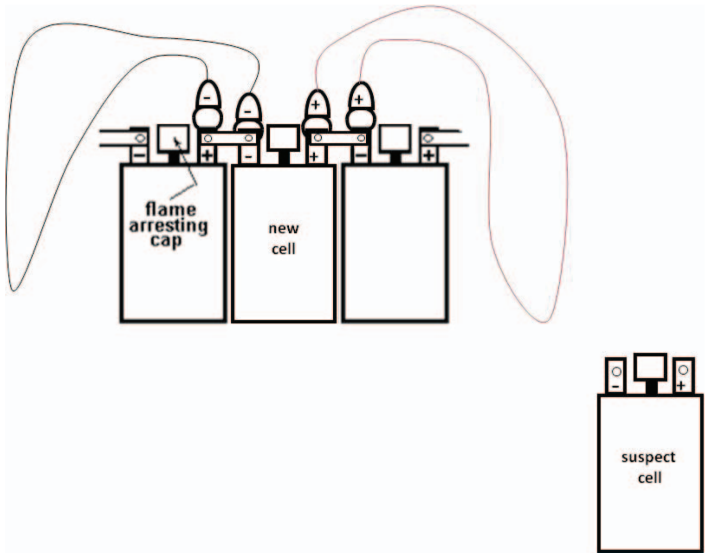

Figure 5 - Intercell Connectors for the New Single-Cell/Module Replacement

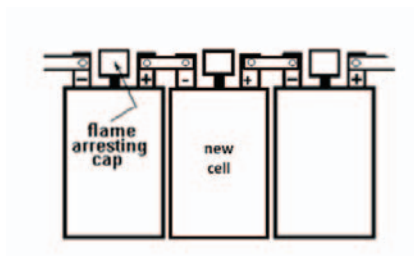

Figure 6 - The Finished Product of an On-Line Single-Cell/Module Replacement

As can be inferred from the pictures, a major concern can exist with having multiple connections (especially when some of those connections are with temporary connectors) with good current-carrying integrity to the same battery cell/module (see Figures 1 and 5), especially when that cell/module only has two small terminal posts. Where there are only two small terminal posts, or there is concern about having enough surface area on the posts and connectors to carry the possible currents, or there is concern about knocking off a temporary connector inadvertently during the procedure, it may be wise to follow the procedures outlined in the "On-Line Bypass" section below, where a larger set of cells is set up around the connection(s) that will be worked on.

On-Line Bypass

The most difficult of the cell/module replacement/bypass types is that where a cell or module needs to be bypassed without disconnecting the string from the DC bus, and while still being able to maintain backup to the loads. The best way to do this in my opinion is with a lead-acid engine start battery because it is capable of handling high currents, is inexpensive, and is ubiquitously available. The recommended steps are as follows:

1. Consult Tables 1 and 2-5 (or calculate per NEC® rules) for the proper cable size to use as a "bypass", and prepare the proper length of cabling with the proper connectors. Prepare the proper bolts, and coat the lugs with a thin film of anti-oxidant. If the bypass cabling is going to run more than a couple of feet, and is of a larger size, it may be wise to plan a method of support for the bypass cabling that will prevent undue strain on the battery posts.
2. Consult Table 7 for the proper size of engine start battery to use (based on Tables 2-5 or the NEC® rules calculations covered previously in this paper). Use one 12 V battery per cell to be bypassed (do only 1 cell bypass at a time; so if there is more than one to be bypassed, repeat this whole procedure for each one). Note that the table gives a 30 second rate that is commonly available, but it is at a low temperature; so at a higher temperature, that same current should be available for a longer time period; hopefully enough to complete the procedure or back out of it. If a longer temporary backup time is desired, choose a larger battery.
3. Wire the temporary battery in parallel to 6 cells (see Figure 7), using temporary cabling sized the same as per step 1.
4. Remove the intercell/module connectors of the cell or module that will be bypassed. **NEVER bypass the cell or module by connecting the bypass cabling first**.
5. Connect the bypass cabling, and use a calibrated torque wrench to tighten the bolts to the battery manufacturer's recommended value.
6. If an entire module was bypassed, or if a stand-alone cell was bypassed, it may be removed from the rack/stand, or this step can wait if the replacement cell/module will be coming in the next several months (in a seismically-qualified configuration, it needs to stay in place to maintain the seismic rating).
7. Adjust the float voltage down until the balancing current flowing between the remaining 5 cells in parallel with the 12 V temporary battery is minimal (us a clamp-on DC ammeter for this step).
8. Remove the temporary engine-start battery and its cabling.
9. Look at the battery manufacturer's recommended float voltage range per cell, multiply it by the number of cells remaining in the string, and if this is a single string configuration, set the DC bus to this level. If this is a multiple string system, it is not as simple. For vented systems where up to 5% of the cells were bypassed, the float voltage can probably be maintained at the existing level (although it can also be turned down a little towards the top-end of the recommended float range for the string with the fewest cells) for several months until the replacement arrives. Maintaining this existing float level will slightly shorten the life of the existing cells in the string with the bypass, and increase its watering interval, but it will maintain the longest possible reserve time of the overall system. For VRLA cells (especially those of the "starved-electrolyte" AGM type), maintaining a higher float voltage increases the risk of thermal runaway and significantly shortens life. In these cases, the float voltage should generally be set no higher than the highest recommended float voltage per cell multiplied by the number of remaining cells in the string that has bypassed cells (in other words, for VRLA battery systems where a bypass occurs, the float voltage almost always needs to be turned down). This will further reduce capacity, but is necessary for safety reasons. Some examples were given previously in this document to help with proper setting of the new float.

Table 7 - Approximate Ampacity of Temporary Bypass Engine Start Batteries

Table 7, Approximate Ampacity of Temporary Bypass Engine Start Batteries	
BCI Group Size	**Avg Cranking Amps @ 32°F for 30 sec to 7.2 V**
U1	375
22	475
3ET	575
24	650
25/35	780
75/86	825
27	900
92	985
30	1000
34/78	1020
31	1050
65	1060
60	1275
4D	1280
6T	1530
8D	1700

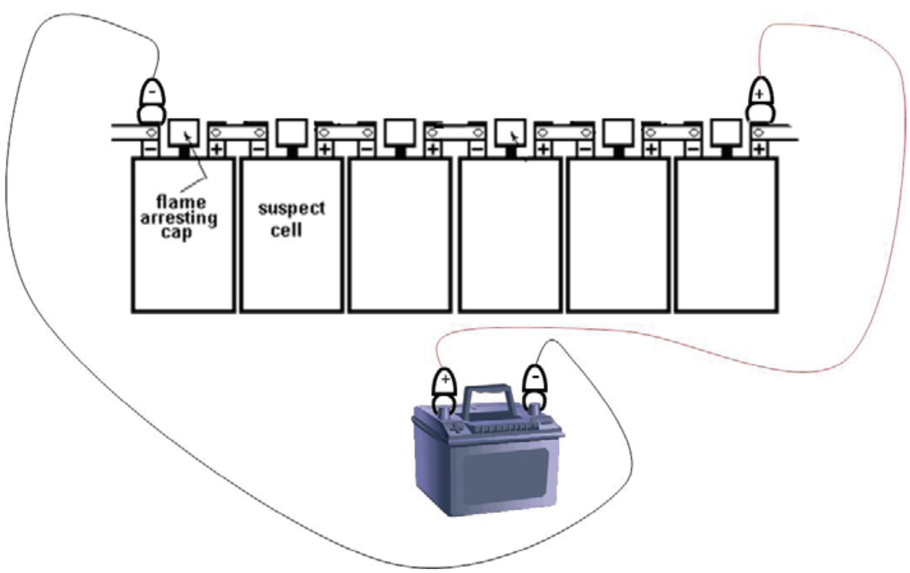

Figure 7 - Temporary Engine-Start Battery for an On-Line Single-Cell Bypass

When the replacement cell/module arrives, follow these steps.

1. Pre-charge the new cell(s)/module(s) if required, per manufacturer instructions.
2. Reconnect the 12 V engine start battery in parallel with 5 cells that include the bypassed cell (see Figure 5, assuming the 2nd cell from the left is bypassed). It is wise to use a properly-rated overcurrent protective device (a breaker or an in-line fuse – fuses are preferred for larger batteries due to their higher k.A.I.C. ratings) in at least one polarity of the paralleled connection to provide short-circuit protection in case a mistake is made.
3. Adjust the float voltage so that a minimal amount of balancing current is flowing in the parallel paths.
4. Remove the bypass cable(s).
5. If the original cell or module that was bypassed was not removed from the rack/stand, do so now.
6. Put the new cell in position on the rack/stand.
7. If the old intercell/module connectors are going to be re-used, clean them properly as needed, and re-apply a thin film of anti-oxidant. If new intercell/module connectors are going to be used, prepare them in a similar manner.
8. Connect the intercell/module connectors, and use a calibrated torque wrench to tighten the bolts to the battery manufacturer's recommended value.
9. Adjust the float voltage so that a minimal amount of current is flowing in the parallel paths.
10. Remove the temporary engine-start battery and its cabling.
11. If the float voltage had been adjusted down to account for the bypassed cell(s), readjust it to its original setting.
12. Either lower the DC bus float voltage to match the voltage of the string/section that is going to be reconnected as closely as possible, or put a charger on the string/section to bring it up to the bus voltage before removing the electrical tape or insulating boots from the connecting cabling, and reconnecting the string. After reconnection, return the float voltage to the final level of Step 11.

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Summary

Replacing or bypassing a cell or module in an incorrect manner can have both short and long-term consequences that are dangerous to personnel, the supported equipment, and the financial bottom line. Following the guidelines in this paper can help to improve the odds that your cell/module replacement or bypass does not cause you heartburn.