REDUNDANT INDUSTRIAL GRADE DC SWITCHING IN A 200 KW BIPV SYSTEM

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ABSTRACT

The newly commissioned 200 kW building integrated photovoltaic (BIPV) system at New York City Transit's Stillwell Avenue Terminal is an example of a redundant design of the DC-to-AC components of a photovoltaic system. NYC Transit brings over 100 years of experience in operating DC systems at voltages comparable to those used in large-scale PV systems. NYC Transit has long-term requirements for operations and places a premium on service reliability. Stillwell Avenue Terminal is the terminus for four (4) subway lines, as well as, the primary base of operations for the Brooklyn-Manhattan Transit Corporation (BMT) Southern Division. Accordingly, Stillwell Avenue Terminal is a functionally critical node in New York City Transit's system. In an effort to mitigate / reduce the risks and impacts to service, redundancy in critical systems is a cornerstone of the Transit's design philosophy. This paper describes the application of this philosophy of redundant system design to a customer-sited BIPV system in the New York Metro area that provides a new benchmark for grid-connected PV reliability.

1. SYSTEM OVERVIEW

The Stillwell BIPV system is a combination of three primary, but overlapping, subsystems. Figure 1 illustrates all three of these subsystems in an overview. The top third of the drawing depicts the canopy integrated array(s). The middle portion of the figure depicts the DC switchgear with its overcurrent protection, switching and instrumentation functions. The bottom third of the figure shows the DC/AC inverters, contactors, switchgrear and related protection equipment. This paper focuses on the unique combination of technical features of these subsystems that provide its redundant operational capability.

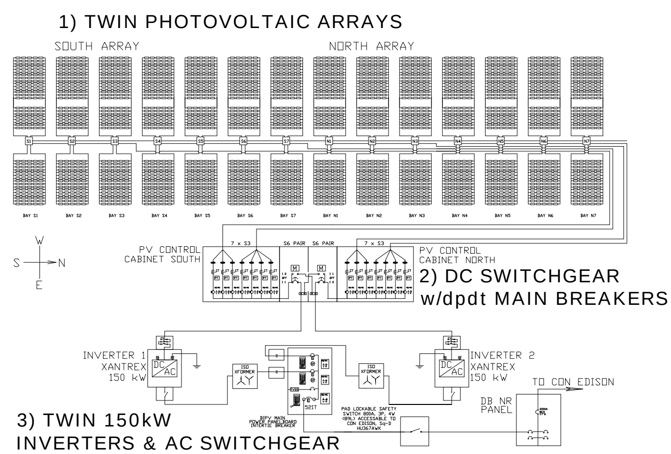

Fig. 1: Three separate subsystems

1.1 BIPV Array

Though they are a part of the same roof structure, there is both an electrical circuit division and a mechanical expansion joint break between the northern and southern halves. Each array is made up of seven bays that run from east to west, spanning the three arches that make up the canopy. Figure 2 is an aerial view from the southeast of the facility that illustrates the overall structure and scale of the arrays. Each of the seven bays is comprised of 39 panels or strings of five laminates. The bays, separated by diamond plate walkways, are designated, from south to north: S1, S2, S3, S4, S5, S6, S7, N1, N2, N3, N5, N6, N7. The total number of laminates in each array is 1365. The total number of laminates in the combined arrays –the full canopy- is 2730.

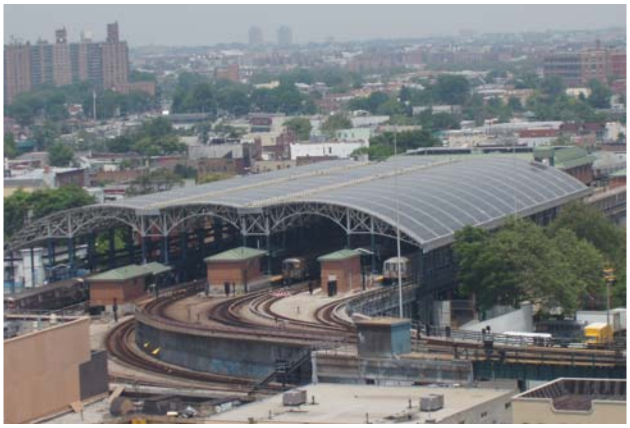

Fig. 2: North-facing aerial view of canopy arrays.

Series laminates per string:	5
Strings per bay:	39
Bays per array:	7
Laminates per array = 5 x 39 x 7 =	1365
Total laminates in canopy = 2 x 1365 =	2730

The outputs of each of the thirty-nine strings are combined in fourteen string combiner boxes (seven for each array) and the outputs of each combiner box, referred to as "PV output circuits", are in turn combined at the PV Control Cabinet (PVCC) to form the total DC output of the arrays.

1.2 DC Switchgear

The second major block in the diagram is the PV Control Cabinet. This is a piece of DC switchgear that performs a number of functions that are key to this unique design. This switchgear serves to combine all fourteen PV output circuits, one for each bay, from the two arrays through the use of fourteen branch circuit breakers. In addition, this device provides switching functionality that allows the arrays to be cross-connected in nine possible permutations through the use of two pairs of interconnected "main" circuit breakers, S8 & S9 and N8 & N9. Figure 3 is a schematic showing the interconnection of these four main DC circuit breakers that result in the ability of the switchgear to direct the output of the arrays to either or both of the inverters. The logic of the mechanical linkage of the circuit breaker pairs permits either breaker in a pair to be closed, or for both to be open, but never for both to be closed. This configuration allows each pair of circuit breakers to provide the functionality of a double pole double throw switch. At the same time this breaker configuration provides overcurrent protection and shunt trip capability. The combination of the first and second sections of the power system shown in Figure 1 result in the delivery of up to an open circuit voltage of 490 VDC and a short circuit capacity of up to 710 ADC at the DC input terminals of either inverter.

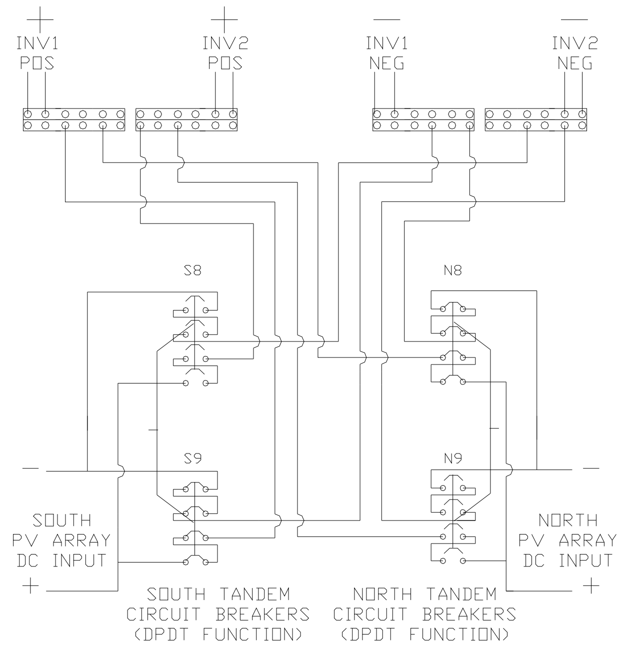

Fig. 3: PVCC Main Circuit Breaker configuration.

In addition to its basic overcurrent protection and circuit isolation and direction functions, the PVCC is the location for 42 transducers, 18 control relays, and 36 sets of dry contacts that interact with the BIPV SCADA system to control and report the status of the DC system.

1.3 AC Power Conditioning Equipment

The third section of the design illustrated in Figure 1is the AC power conditioning equipment. This is comprised of the inverters, isolation transformers, contactors and BIPV Main switchboard. The inverters serve to convert the DC electricity of the PV arrays into AC electricity that is compatible with the electric grid. As with the PV Control Cabinet on the DC side, the BIPV Main switchboard combines the AC output of the inverters and connects it, through the 800 Amp intertie breaker, to Con Edison's service the at one of the facility's main switchboards. The entire AC output of the combined PV arrays is channeled through an 800 Amp, manually operable, lockable, AC disconnect. The theoretical maximum AC output of the combined inverters is approximately 490 Amps at 208 VAC.

Two Xantrex 150 kW inverters were selected for this design. These inverters are designed to incorporate the safety features of standards IEEE-929 and IEEE 1547, and UL 1741. These inverters are designed only to operate in the presence of the utility grid such that in the event of a power outage (voltage collapse) they will shutdown in six cycles (0.1 second.) They do not have the capability of operating in a "stand-alone" mode or as an upinteruptable power supply (UPS.) Adherence to these standards assures that utility line workers are protected from unanticipated voltages back fed from the customer's site during power outages.

The inverter's control circuitry is also specially designed for operation with photovoltaic systems to extract the maximum power from the, often variable, solar resource. The inverters use a user-adjustable maximum power point tracker (MPPT) control algorithm to extract the maximum available energy for the array. Once their operating parameters have been programmed they are fully automatic and require no external control.

2. INSTRUMENTATION & SCADA SYSTEM

2.1 SCADA Performance Monitoring

The Stillwell BIPV system has been instrumented to monitor all of its component sub-systems, both AC and DC, and provide these inputs to a central Supervisory Control And Data Acquisition (SCADA) system. The sensor, transducers and digital monitoring components described here connect to the remote terminal unit (RTU) where programmable logic controllers (PLC) digitize the analog signals and interpret the digital signals in order to relay them to the central computers of the BIPV SCADA system. In addition each of the 14 photovoltaic source circuits is individually monitored by its own ground fault detection relay.

The SCADA system monitors the PV output at 182 points in the array, as well as at the inverter input and output locations, and other critical points in the electrical balance of system. The SCADA system also tracks weather and insolation data in order to validate the system's performance. The instrumentation system is configured much the same as is typical of factory process control systems in that it uses sensors distributed throughout the array. Each combiner box possesses 13 Hall Effect current transformers whose analog output is digitized by a networked analog to digital converter/multiplexer. The resulting data stream is continually fed to the RTU. Each of the Hall Effect current transformers measures the combined current of three strings of laminates. At any point in time the SCADA system user can deduce the "health" of a set of three strings by comparing it to adjacent sets to its immediate north and south. This level of instrumentation allows, at a minimum, the user to view the system at a resolution of less than one percent of its total capacity.

2.2 Protective Relaying

The Stillwell Avenue Terminal is sited on a network grid and as a consequence Con Edison requires that independent power generation systems comply with a strict set of interconnection protocols to monitor and limit reverse power flow. All power generated within the facility must be consumed on site. The Stillwell PV SCADA system is therefore equipped with two reverse power relays to prevent the export of power to the utility grid. These protective devices monitor over and under frequency, over and under voltage, and directional power. If the power flow into the facility ever drops below a present level the protective relays trip the main AC circuit breaker.

3. REDUNDANT DC SWITCHING

The Stillwell BIPV system is almost fully automated. Once the system has been configured there is generally little or no need to reconfigure any settings. It is possible, however, to manipulate the four main switches in the PV Control Cabinet to direct the output of the arrays to either or both of the inverters. In addition it is possible to shut down either of the inverters by disconnecting them from the BIPV Main Switchboard, either by manually opening their respective circuit breakers or by opening their respective contactors. Both of these systems, the AC circuit breakers and the contactors, can be controlled manually in the BIPV equipment room, or they can be opened remotely through the user interface of the SCADA system. This capability means that, in the event of a failure or scheduled maintenance event for either of the inverters, the system can be configured to operate, at or near full capacity, using the remaining inverter.

The four main circuit breakers in the PVCC, N8, N9, S8, and S9 (these designations correspond to North 8, North 9, South 8, South 9) provide the ability to isolate either of the inverters from the array or direct the total array output to a single inverter. The positions of these breakers control the connection of the combined north and south array output and how it is directed to the inverters. There are a total of nine permutations of breaker position and direction of DC energy flow from the PV array to the inverters.

Figure 4 is a Truth Table that describes the nine switch permutations and the connections from the arrays to the inverters that result. Each "Case" in the left-most column of the Truth Tables represents one of the possible nine switch combinations. The four columns to the right of the "Case" column represent the inputs or switch positions. A "1" represents a switch that is ON. A "0" represents a switch that is OFF. (Note that the engraved labeling on the switches themselves uses this same nomenclature: 1 = ON, 0 = OFF.) The far right four columns represent the output or outcome of the switch positions on the left. For example in Case 1 we have switch S8 closed, switch S9 open, switch N8 closed, and switch N9 open.

	CIRCUIT BREAKER				INVERTER			
Case	S8	S9	N8	N9	Inverter1	Inverter2	Inverter1x2	Inverter2x2
1	1	0	1	0	1	1	0	0
2	1	0	0	1	0	0	0	1
3	0	1	1	0	0	0	1	0
4	1	0	1	0	1	1	0	0
5	1	0	0	0	0	1	0	0
6	0	0	1	0	1	0	0	0
7	0	1	0	0	1	0	0	0
8	0	0	0	1	0	1	0	0
9	0	0	0	0	0	0	0	0

Fig. 4: PVCC Main Circuit Breaker Truth Table.

The result of this combination of switch positions is that the south array power is directed to Inverter 2 and the north array power is directed to inverter 1. The two far right columns represent an outcome where we have both arrays directed at a single inverter. Figures 5 and 6 illustrate "Case 1" and "Case 3"and the resulting circuitry.

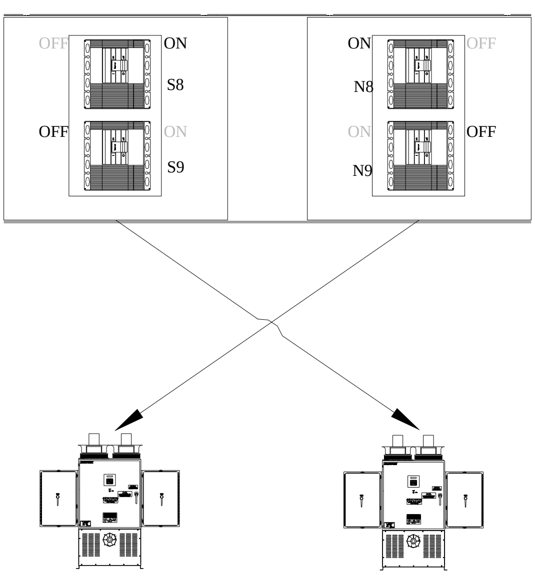

Fig.5: South Array to Inverter 2 & North Array to Inverter 1

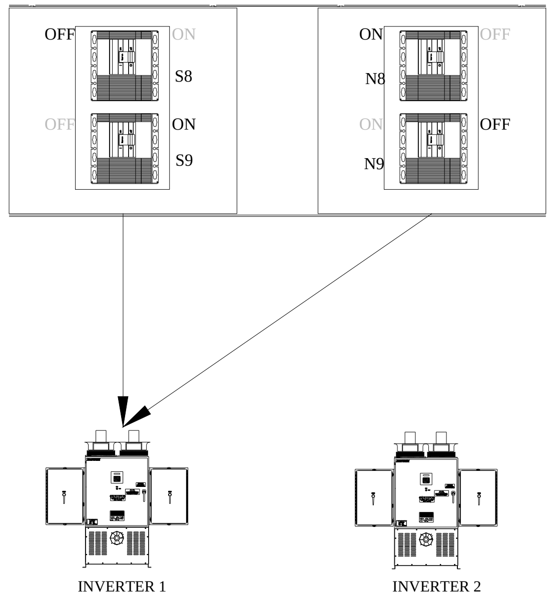

Fig. 6: Switch Settings South & North Arrays to Inverter 1

4. <u>PROJECT TIMELINE</u>

The Stillwell photovoltaic installation was just a small part of a much larger renovation project which included the demolition of the original station and construction of the new one, all without ever closing station service completely. The BIPV system was several years in planning and development prior to the installation of the first laminate. Much of the initial schedule was dictated by the installation of the steel structure of the canopy and the installation of the tracks at the platform level. Once the canopy was completed the installation of the modules and accociated wiring took about one year. The final timeline for the installation and commissioning of the system is listed in figure 7.

Stillwell Completion Timeline	
Complete array wiring	5/9/2005
DC pre-operational test	5/30/2005
AC pre-operational test	6/3/2005
As-built and O&M manual finalized	8/31/2005
System training & commissioning	9/19/2005
Con Ed acceptance	9/19/2005
Final maintenance training	9/29/2005
Official start of operations	11/22/2005

Fig. 7: Stillwell BIPV system final completion schedule

5. CONCLUSIONS

The Stillwell Avenue Terminal BIPV system provides a case study for the photovoltaic industry in redundant power system design. Using relatively simple and readily available power circuit components this system achieves a level of redundancy heretofore unavailable in grid-connected installations.

Fig. 8: Stillwell Avenue Terminal

6. ACKNOWLEDGMENTS

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