# Final Scientific Report for DOE/EERE

**Project Title:** Cascaded Micro Inverter PV System for Reduced Costs

**Covering Period:** **Final**
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## *Final Report Summary and Format*

The intent of this report is to provide the final conclusions and disposition of the "Cascaded Micro Inverter PV system for Reduced Costs" SEGIS-AC project. Because of product commercial limitations, this project received a "no-go" decision from the Department of Energy (DOE) for Budget Period 2 (BP2) and beyond. This decision by the DOE was reached with Delphi's concurrence, after details regarding installed system cost and PV inverter limitations were disclosed. In the opinion of Delphi, these issues severely limited the overall commercial viability of the inverter. The commercialization aspects of the project were a key deliverable throughout the project. These conclusions will be further detailed in this report. This report pulls details from the prior quarterly reports and Budget Period 1 (BP1) go/no-go exit presentation. Within this report, material contained within these documents will be referenced.

The following objective and background sections restate the initial positions on this project.

## *Original Project Objective*

In this project, a team led by Delphi will develop and demonstrate a novel cascaded photovoltaic (PV) inverter architecture using advanced components. This approach will reduce the cost and improve the performance of medium and large-sized PV systems. The overall project objective is to develop, build, and test a modular 11-level cascaded three-phase inverter building block for photovoltaic applications and to develop and analyze the associated commercialization plan. The system will be designed to utilize photovoltaic panels and will supply power to the electric grid at 208 VAC, 60 Hz 3-phase. With the proposed topology, three inverters, each with an embedded controller, will monitor and control each of the cascade sections, reducing costs associated with extra control boards. The above details were modified as analysis and design efforts identified opportunities to optimize cost and performance trade-offs.

## *Original Project Background*

The Solar Energy Technology Program is leading the DOE's SunShot initiative to reduce the installed cost of utility scale photovoltaic (PV) systems to $1 per watt. PV inverters are expensive, insufficiently robust, and inefficient. The modularity and low cost of multilevel inverters positions them as a prime candidate for the next generation of efficient, robust, and reliable grid connected solar power electronics. The cascaded inverter architecture, discussed in this report, will also provide reactive support and smart grid capabilities that enhance grid stability. By deploying this architecture, system reliability is enhanced and production costs are lowered and renewable energy can be deployed that is an asset to the smart grid. For these reasons, the work proposed in this report has high potential for achieving the reduced cost and efficiency goals defined in the SunShot initiative.

## *Final Disposition*

This report details the final disposition of this project. The Delphi team presented to the DOE the significant commercial challenges discovered during the course of executing the project. At the conclusion of that review, the DOE, along with Delphi, concluded that the project would be terminated at the conclusion of BP1. This conclusion was supported by Delphi and is a result of the installed system cost estimates and the overall impact on the inverter's commercial viability. The details on the cost impact derived from the design and installation analysis are summarized in this Final report under the appropriate Budget Period 1 Task outlined below. In Delphi's opinion, the limitations associated with this technology are primarily associated with the installation cost challenges and installation architecture requirements. These cost numbers are summarized below under the appropriate task.

## *Significant Accomplishments—Project Final*

### Task 1 - Develop Preliminary Requirements and Analyze Alternative Design Options for the Inverter System, Cascaded Inverter Architecture, PV System Controller/ MPPT Strategy, and Modular H-bridge Design

At the conclusion of the project, Delphi had invested significant work in developing the requirements and initial design concepts for the cascaded multi-level inverter. Summary requirements are shown below. The inverter mechanical design concepts considered multiple enclosure options intended to maximize environmental robustness while minimizing cost. In addition, consideration for the thermal requirements of the inverter were analyzed, modeled and designed into the enclosure. During the PQ5 reporting period, the team continued to analyze the mechanical design details and thermal dissipation requirements. These results have been summarized below and were presented to the DOE at the Go/No-Go review in Knoxville on October 29, 2012. As concluded and presented to the DOE, the mechanical design had matured enough to determine the original mechanical part costs were underestimated when compared to the original assumptions made by Delphi. The initial thermal estimate and mechanical design implemented the required H-bridge sections with $D^2$ FET packages cooled with thermal vias through the inverter circuit board. Further analysis of the required heat dissipation necessitated the use of TO220 FETs, electrically isolated, but directly clamped to the inverter heat sink. This approach increased the cost of the estimated mechanical enclosure when compared to the original proposed design that Delphi studied at the time of project submission. The price increase associated with the mechanical requirements was estimated at 2.4 cents per watt and is associated with both an increase in the actual mechanical parts and the labor to mount and assemble the numerous FETs to the housing. The mechanical design is shown later in this section along with the mechanical design table. The sections below outline the fundamental requirements that were developed as part of this project.

## *Product Overview*

The primary function of the product is to process DC power generated by Photovoltaic (PV) panels and transfer it into the public utility grid as 60 Hz (US version) AC power. Note that this design does not consider net-metering issues and it is intended that 100% of the power generated be sent to the utility grid via a transformer.

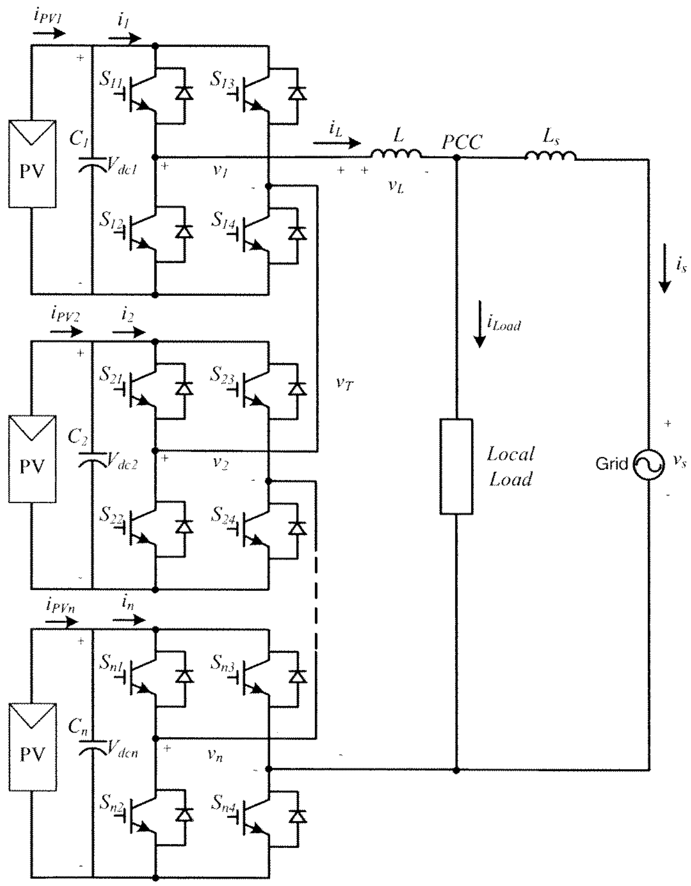


Figure 1: Cascaded Multilevel H-bridge Inverter

Figure 1 shows a diagram of a basic single-phase cascaded multilevel inverter. The IGBT symbol is to be considered as an electronic switch and not necessarily as an IGBT. The diagram is generalized for an inverter of "n" bridge blocks. For a 5-bridge inverter, this diagram shows bridges 1, 2, and 5; with bridges 3 and 4 being implied. The inverter system consists of 5 full-bridge (H-bridge) blocks, each of which accepts input power from a sub-string of PV panels. The inverter outputs power at 120 $V_{AC}$ (L-N). Three of these inverters can be combined to provide 208 $V_{AC}$ 3-phase power. Or two of these inverters can be combined to provide 240 $V_{AC}$ split-phase power. The inverter operates by treating small sub-strings of PV panels as floating voltage sources which are switched in a series configuration to produce a facsimile of a sinusoidal waveform. The output of the series configuration is connected to a power inductor and the line voltage such that the series-connected full-bridge elements are used to adjust the voltage across the inductor in order to provide power to the line with the current in phase with the voltage. Please refer to Figure 2. The system is enclosed in a housing that provides cooling, mounting and protection from the environment. Note that other numbers of bridge blocks (than 5) could be used and might be beneficial under certain circumstances.

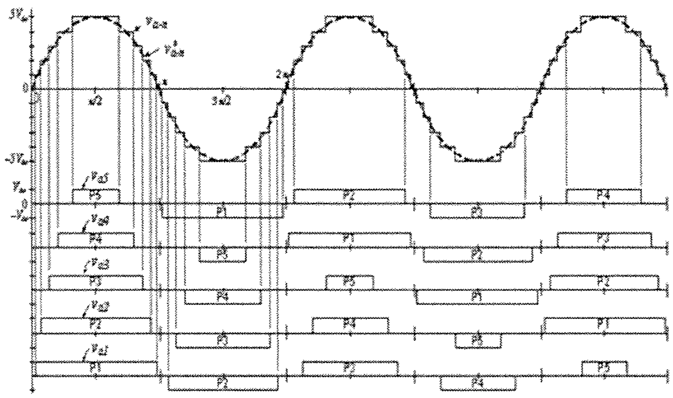

Figure 2: Rudimentary 5 bridge (11 level) inverter waveform (detailing possible operation of each bridge section)

### *Product Specifications*

| | |
|---|---|
| **Rated output power:** | *6600 Watts* |
| **Input voltage:** | *90 Vdc max. per H-bridge section (x 5 Bridges)* |
| **Nominal output voltage:** | *120* $V_{AC}$ *RMS 60 Hz line-to-neutral (balanced neutral)* |
| **Efficiency:** | *96% min. at rated power* |
| **Ambient temperature:** | *65°C* |
| **Cooling:** | *Natural Convection* |
| **Housing:** | *Rain-tight, PV rack-mounted (shaded)* |
| **DC connections:** | *5 +/- pairs of MC4 connectors on 200mm pigtails*<br>*Possible snap-on frame to orient and align connectors*<br>*Presume connectors will suffice as DC disconnect* |
| **AC connections:** | *Bolted – cover and seal details TBD*<br>*Separate AC disconnect presently assumed* |
| **Communications:** | Power Line Communications (*PLC) – details TBD* |

### *Electrical Concept*

A string of 2 or 3 panels in series (depending on the number of cells/panel) will provide a maximum power point (MPP) voltage in the range of 40V to 90V. It is expected that these strings will consist of 3x54 cell, or 2x60 cell, or 2x72 cell panels. 2 or 3 those groupings (for a total of 4 or 6 panels per sub-string) in parallel will be considered as a single dc source for the inverter. This grouping of 4 or 6 panels will be called a sub-string.

The inverter system is based on the series connection of H-bridge "blocks" with separate floating DC sources. An H-bridge is comprised of four MOSFET switches with the input of the bridge consisting of the sub-string of PV panels. The output of the H-bridge is connected to the bridges above and below the subject H bridge. Please refer again to Figure 1. Note that the switches in this design are actually two transistors in parallel. Hence a bridge block of 4 switches is actually 8 transistors. The four switches in each H-bridge block are controlled such that only two of the four switches are turned on at any time. Each bridge block generates three discrete outputs: +V, 0, or –V (where V is the voltage of the PV sub-string). Using 5 bridge blocks (controlling 5 of the afore-mentioned PV panel sub-strings), each set of source panels will be series connected in a positive polarity, or a negative polarity, or a “straight though” bypass of the panel sub-string. Please refer again to Figure 2. The output phase voltage is synthesized by the addition of voltages that are generated by each block. This configuration will produce up to an 11-level “stair stepped” voltage waveform. The maximum number of output phase voltage levels “x” in a cascade inverter with n separate dc sources is $x = 2n + 1$. Since the switches do not share the same load when generating the stair stepped waveform, they will need to be “rotated” by some scheme to share the duty cycle and provide power at maximum power point (MPP) for the particular sub-string. Additionally, capacitors will be required to store the output of the individual sub-string when it is not delivering power through the inverter.

Modulation will be performed at the step-points to reduce generation of distortion and harmonic products. See Figure 3. Fewer steps will be used when the PV string is producing higher voltages. Note that the voltage produced by typical PV cells can vary over a range of approximately 2:1. Illumination and cell temperature have a large influence on the voltage delivered by the PV cells.

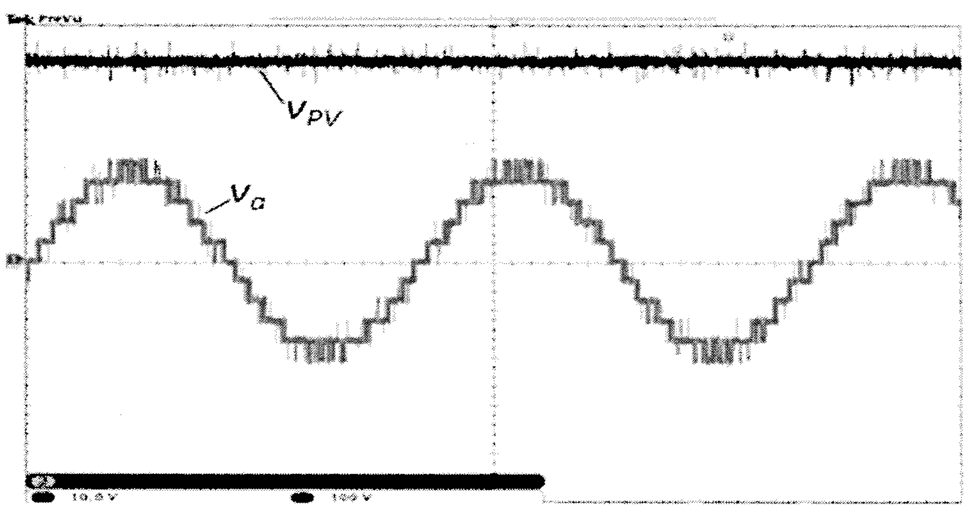


Figure 3: 11-Level Inverter Output Voltage (pre-filter)

The control strategy can allow for varying amounts of power to be delivered by each sub-string hence each sub-string can be managed at maximum power point (MPP) for the composite of that individual sub-string. Since power delivery from each sub-string to the AC output varies throughout the 60 Hz AC cycle, the power delivery to each bridge section will have a ripple component at 120 Hz and related frequencies. Power delivery from the PV panels will need to be buffered from this ripple component by a DC filter – mostly composed of capacitors.

Under certain conditions of a sub-string, an over voltage condition might appear across the MOSFET switches. No load on very cold illuminated PV panels is an example of such a situation. An over voltage protection circuit could be considered to protect the 100V-rated MOSFET switches. Sensors will also be included in the system to sense the PV voltage and current, and to communicate those values to the inverter controller.

### *Considerations*

Several possible cases were studied to determine the impact of several different approaches to this inverter. Even though many other combinations of the various considerations are possible, the examples analyzed seemed adequate to point out the desirable design direction.

### *Scale of the Inverter*

Scale-volume (units built) tradeoffs are often misunderstood and exaggerated one way or the other, Larger scale units have economies in requiring fewer housings and controllers than an equivalent capacity of a smaller-scale inverter. But the larger components involved often carry a high price premium (large enclosures, power switches, etc.). Smaller-scale units have some economies that go with higher volume of production (thought this is also often overestimated). The cost of power switches at the smaller scale can be a VERY significant factor in favor of the smaller scale inverters. There are also some balance-of-system (BoS) cost considerations that will be addressed elsewhere in this document.

Five concepts were considered for the inverter. A preliminary Bill of Material (BoM) cost was estimated using pricing of all the components for each option. This allowed for a dollars-per-Watt comparison of the different-scale inverters. The cost of switches associated with each H-bridge block, combined with keeping the several DC paths short, and size of the mechanical housing appear to favor the smaller power inverters (<10kW for a single phase). A common price/BoM-cost factor of 2 was assumed for all the options. Balance of System (BoS) implications were kept in mind, though not quantified in this analysis. Also efficiency estimates were calculated for each of the concepts; major losses – conduction losses, switching losses, inductor and filter losses, etc. were accounted for in the efficiency. All options were considered to contain all 5 brides in a single housing. This eliminated the need for high-speed synchronization between separate physical units.

### *MOSFETs vs. IGBTs (and other switch technology considerations)*

The most significant factor for opting for MOSFETs over IGBTs for the inverter was efficiency. The inverter operation would cause significant conduction losses and this does not favor the IGBTs (since the current is passed through such a large number of switches). Several IGBTs from major suppliers were considered. The topology of the cascaded multilevel inverter considered for this design incorporate a high switch count compared to other topologies and this dictated the use of MOSFETs at their "sweet spot". That is the best price-benefit point; i.e. low $R_{dson}$ at a good price. This directed the use of 100V or lower MOSFETs. The large switch count and distributed losses allows a thermal system with modest performance to be used, also benefitting cost. Note that a 5-bridge inverter requires 20 switches. For the 6600 W inverter case, however, a switch is comprised of 2 MOSFETs in parallel. This results in 40 MOSFETs to provide switches for a 5-bridge inverter.

In order to gain the maximum advantage in efficiency and cost offered by MOSFETs, the 100V range was identified and a detailed cost/benefit study was done. IPx100N10S3-05 was identified as a cost-effective option (available in both $D^2$PAK and TO-220 packages). Considering a grid connected PV system using three of these inverter systems to generate a three phase AC voltage, the lowest cost solution would appear be 208 $V_{AC}$ (line-to-line; 120 $V_{AC}$ line-to-neutral) 3-phase output. This approach also allows for the configuration of 1-phase 240 $V_{AC}$ split-phase systems with the same sub-modules. Transformers of up to 500 kVA can be used to transform 208 V 3-phase (Y-connected) to 13 kV levels. It is recognized that collection of AC power at this lower voltage will result in some additional cost in Balance-of System costs. Figure 4 depicts a 3-inverter 20 kW implementation. In a likely system the outputs of multiple inverters will be combined at 208 V before being transformed to 13.8 kV by a large transformer. The transformer provides galvanic isolation between the panels and the utility grid.

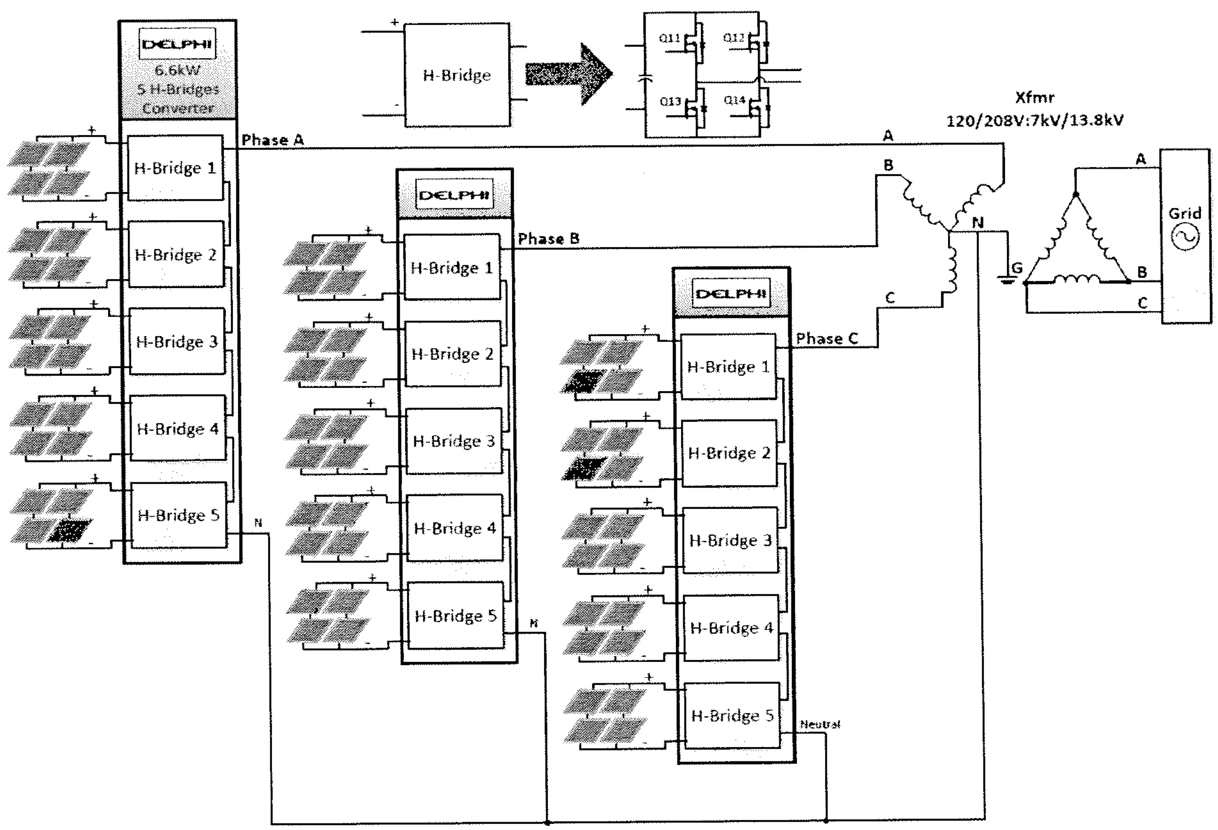


Figure 4: combination of three 1-phase inverters to supply 3-phase power

Figure 5 summarizes the results of the study performed. The 6600 Watt inverter provides the best cost and price – at least by the rules of the study as it was performed.

**Cascaded Multi-Level Inverter**
**Efficiency and Cost Table**

| Option | Phase | Description | Size(W) | Calculated Efficiency | BOM Estimate | Price Factor | Sale $/W |
|---|---|---|---|---|---|---|---|
| 1 | Single | 1 panel/H-bridge, MOSFET, D2PAK | 1,476 | 97.7% | $273 | 2 | $ 0.369 |
| 2 | Single | 120V, 1-phase, MOSFET, 5x6mm | 3,322 | 97.3% | $280 | 2 | $ 0.168 |
| 2a | Single | 120V, 1-phase, MOSFET, D2PAK | 6,643 | 96.1% | $352 | 2 | $ 0.106 |
| 3 | Three | 480V, IGBT, TO-247 | 23,500 | 92.7% | $2,392 | 2 | $ 0.204 |
| 4 | Three | 480V, IGBT, 100A Modules | 55,400 | 93.1% | $10,968 | 2 | $ 0.396 |
| 5 | Three | 480V, IGBT, 400A Modules | 184,500 | 94.2% | $25,750 | 2 | $ 0.279 |

Note: Option 1 requires a special matching transformer.

Figure 5: BoM cost and price for cascaded multilevel inverter

### *Balance of System*

There is a marked difference in the wiring of the cascaded multilevel inverter system compared to other architectures. In comparison to a central inverter, this inverter system will utilize short DC wires that run to the inverter since the inverter will be mounted on the racking - immediately under the panels. The number of DC connections depends on the final PV panel configuration, but in general each sub-string has to be connected to a module and therefore, the inverter system will require 5 pairs of DC connectors coming to the inverter. Thus the number of connections will be high and this will impact DC installation labor and materials.

The architecture of this system also has BoS implications on the AC side. There is more material and labor on this side of the inverter, also. The AC wiring and labor associated with getting AC power conduits from the inverters to the AC combiners/AC electrical panel will increase as the inverter count is scaled for larger photovoltaic installations.
See Figures 6 and 7 for an example of a possible implementation of a 200 kW solar field. Note that in this example the installation plan does not consider the cost reductions possible from handling the three phase output from groups of inverters as a 3-phase entity (that is each single phase output is considered a separate entity and is run in an individual conduit to the single combiner at the transformer). In addition, the system plan does not consider the improvements that might be available by using distributed AC combiners.

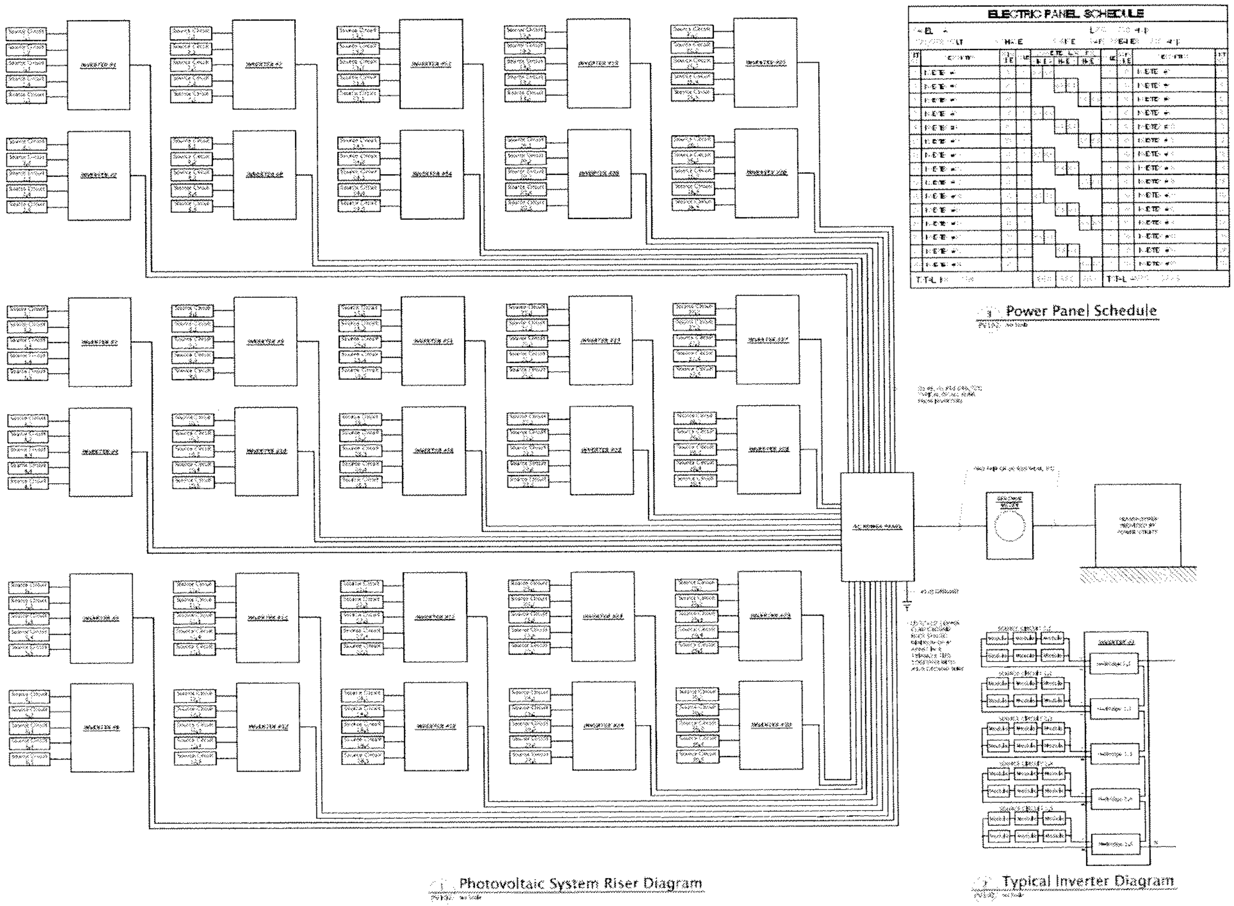


Figure 6: schematic representation of a 200 kW installation of 6600 W inverters

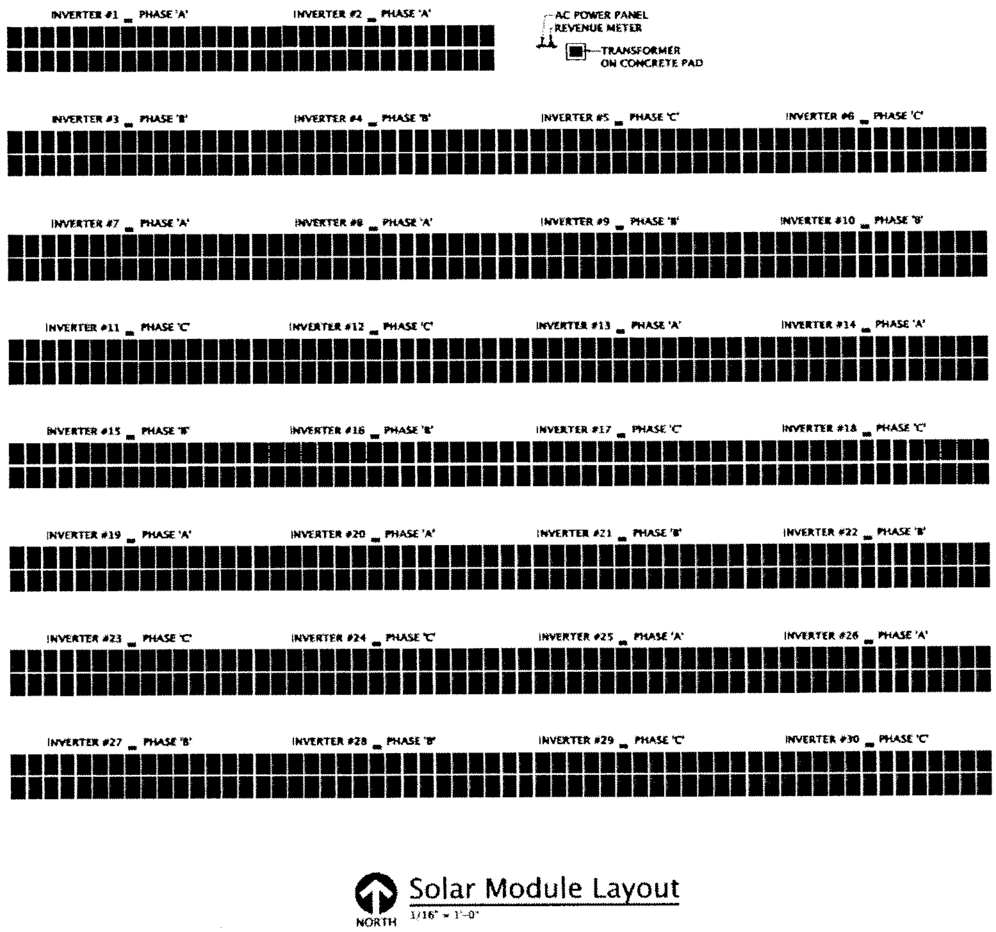


Figure 7: possible site physical layout for a 200 kW installation of 6600 W inverters

## *MECHANICAL CONCEPT*

Note that the mechanical concept has been refined somewhat since the cost study was performed. As a result, the mechanical BoM cost is higher than in the analysis shown in Figure 5. The system will be enclosed in a housing that provides adequate protection from the elements (rain-proof), ample cooling, and mounting capability.
The housing will contain an entire 5-bridge inverter. The components include one circuit board – 6 layers FR-4, 2 oz copper, and 1.6 mm thick. The board will be mounted directly on the housing. The housing will also provide the connection system which consists of the five pairs of DC inputs and one AC output. Plastic terminal block headers might be considered in the future instead of off-the-shelf plug-in headers. However for the time being connections will be presumed to be 5 pairs of MC4 connectors on pigtails.

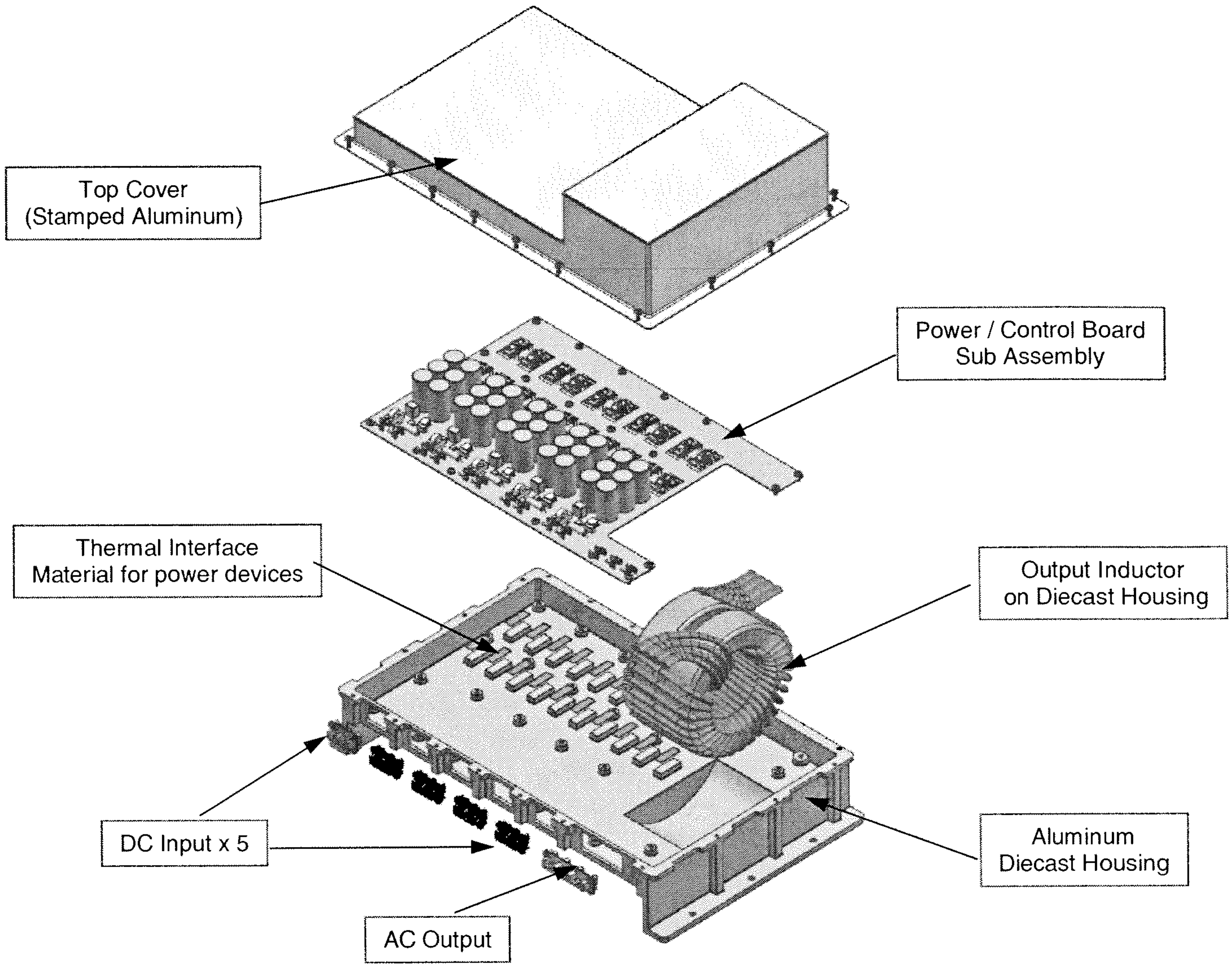


Figure 8: Preliminary Packaging Concept – Die cast Aluminum

Two options were considered for the preliminary packaging concept:

- Die cast Aluminum / Stamped Aluminum Cover
- Steel frame / Extruded Heat sink / Stamped Aluminum Cover

Since the system is intended to be cooled by natural convection of air, effective cooling of the hot components required a rather large die cast housing. The second option showed better cooling and is estimated to be significantly less expensive.

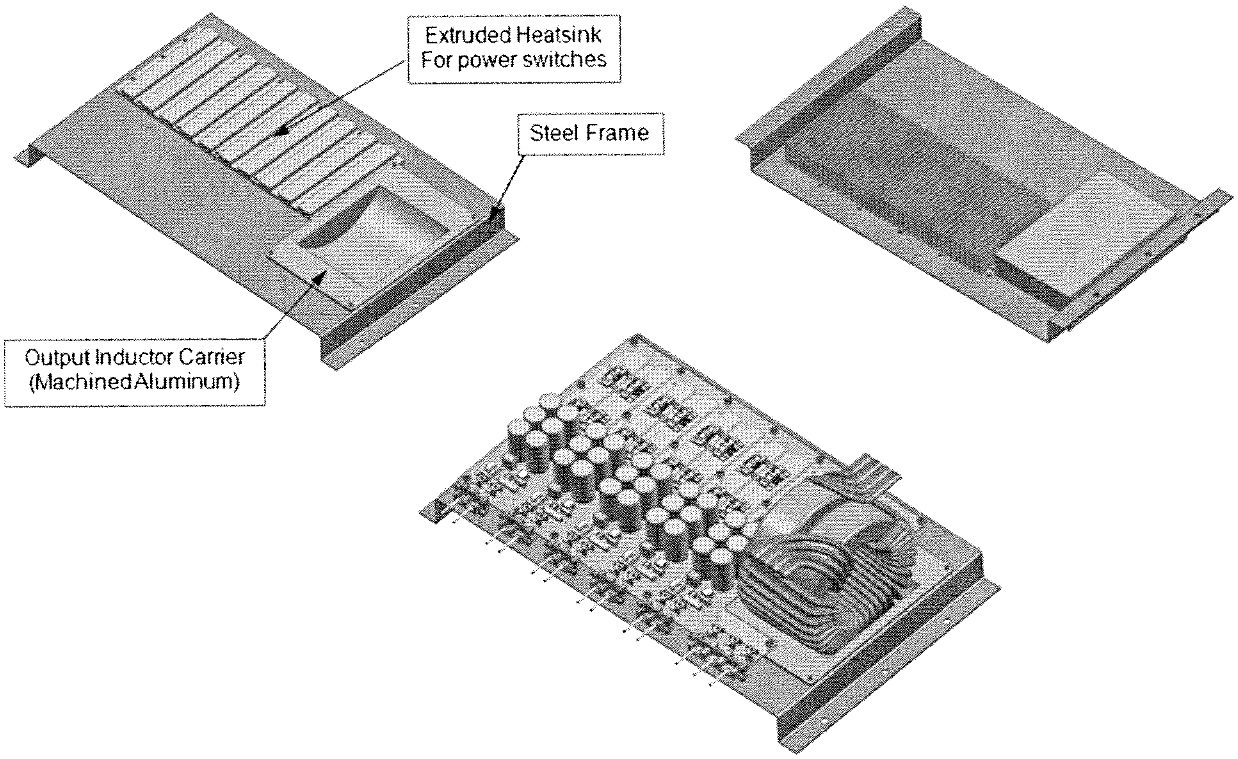


Figure 9: Steel Frame – Extruded Heat Sink Concept

### *Thermal Analysis*

The system was analyzed for outdoor mounting with an ambient temperature of 65°C. The MOSFETs were directly mounted on the heat sink through a ceramic dielectric (.6 mm aluminum oxide) interface and thermal adhesive on both sides of the dielectric (for case with extrusion) or thermal adhesive and thermal grease on the dielectric (for case of the casting). Since the layout is intended to be symmetrical across the entire circuit board the thermal analysis was performed for only one of the FET assemblies.

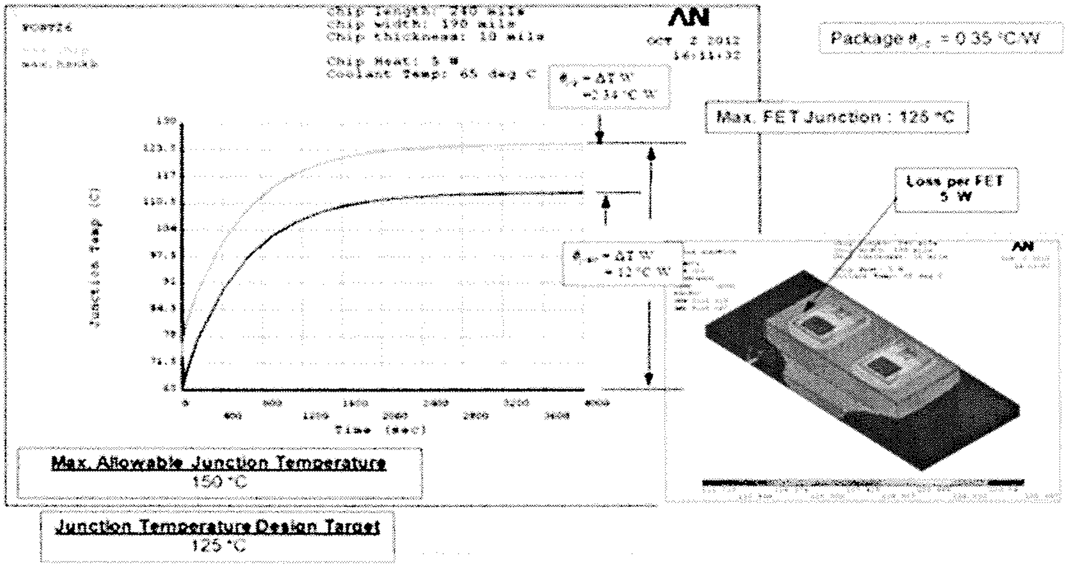


Figure 10: Al Die cast Fin

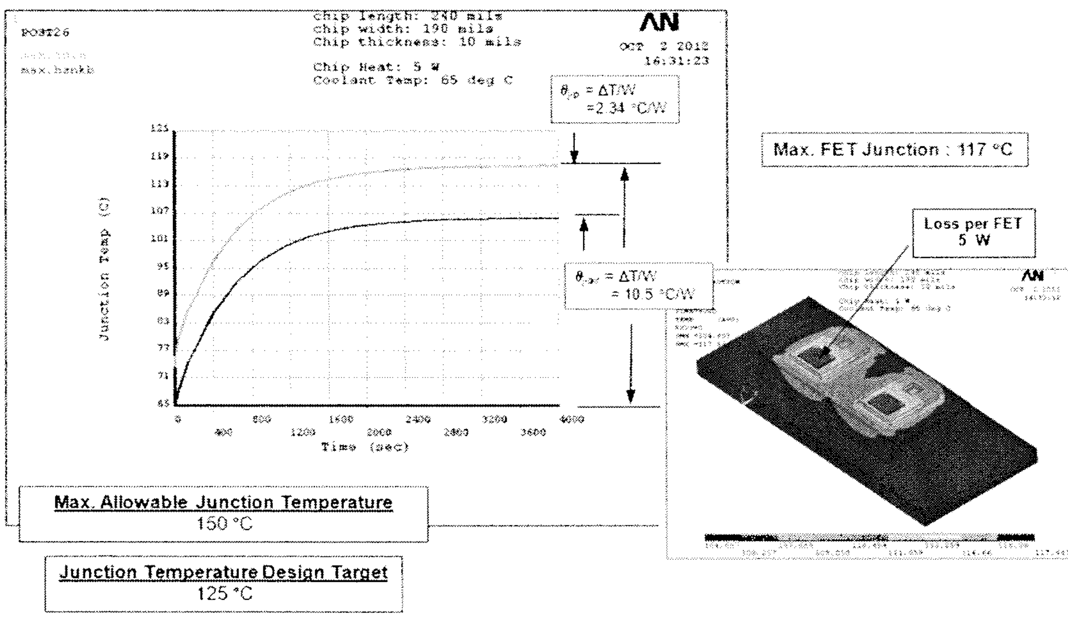


Figure 11: Al Extruded Fin

## *COMMUNICATIONS*

A means to collect appropriate data on the power harvested from the PV panels will be provided. The system will be able to monitor for fault conditions and communicate all relevant data to the user via power-line communications (PLC). Details of this communication interface were not yet determined at the time of this report. The important feature here is the avoidance of any dedicated signaling connections.

## Task 4 - Perform Bench Level EDU Verification Testing

As documented in both PQ4 and PQ5 the UTK team invested significant effort in bench level verification testing of the EDU PV system. This work by the UTK team was critical in developing the final requirements for the phase 2 prototype system. The analysis of the EDU system has been provided in prior quarterly reports and the BP1 go/no-go review. The final summary from PQ5 is shown below.

As was documented in PQ4, a three-phase modular 11-level cascaded inverter has been built at UTK. Grid-connected tests have been conducted to show that the output voltage is synchronized with the grid and that low THD current with unity displacement power factor can be provided. To complete the functional testing, individual MPPT control is applied to the three-phase multilevel inverter to reduce the adverse effect of PV mismatches and improve the overall efficiency of the PV system. Meanwhile, PV mismatches could introduce unbalanced power supplied to the three-phase grid-connected system. Since the grid voltage is balanced, the different input power among different phases will cause unbalanced current to the grid, which is not allowed by power quality standards. Thus, modulation compensation is introduced to balance the grid current.

A three-phase 7-level cascaded H-bridge inverter has been tested. Fig. 12 shows three dc-link voltages of phase *a*. It can be seen that each dc-link voltage is controlled independently, which means individual MPPT can be achieved. The inverter output voltage waveforms are presented in Fig. 13. With the modulation compensation, a zero sequence voltage is imposed upon the phase legs. The inverter output voltage is unbalanced proportional to the supplied power of each phase, which helps to balance the three-phase grid current. As shown in Fig. 14, PV mismatch happens and the supplied PV power to the three-phase system is unbalanced, the three-phase grid current is still balanced.

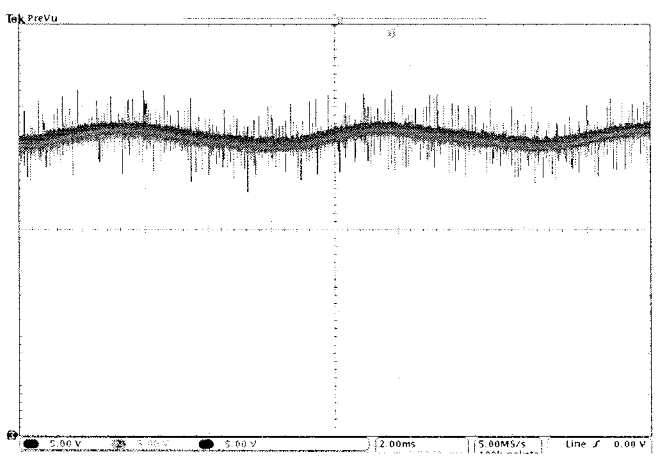


Figure 12. DC-link voltages of phase *a*.

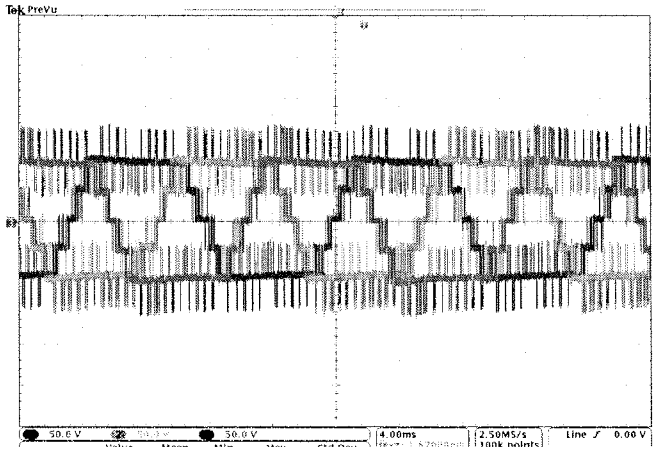

Figure 13. Inverter output voltage waveforms with modulation compensation.

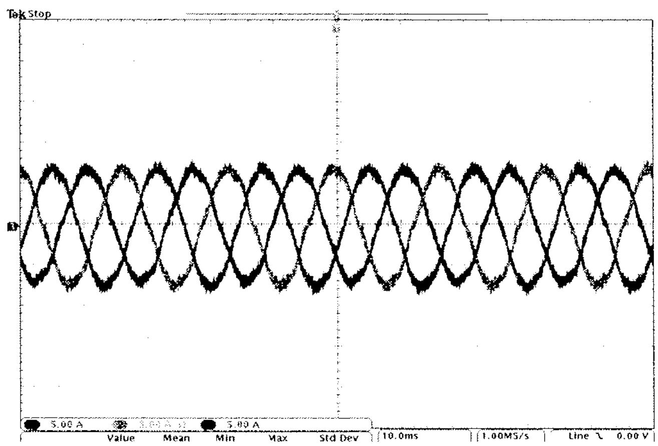

Figure 14. Experimental grid currents with unbalanced PV power.

Figure 15 shows the grid voltage and current waveforms of phase *a*. It can be seen that the grid current has the same phase as the grid voltage and has unity displacement power factor. The THD of the grid current is 4.6%, as shown in Fig. 16, which is less than 5% and meets power quality standards, like IEEE 1547 in the U.S. and IEC 61727 in Europe.

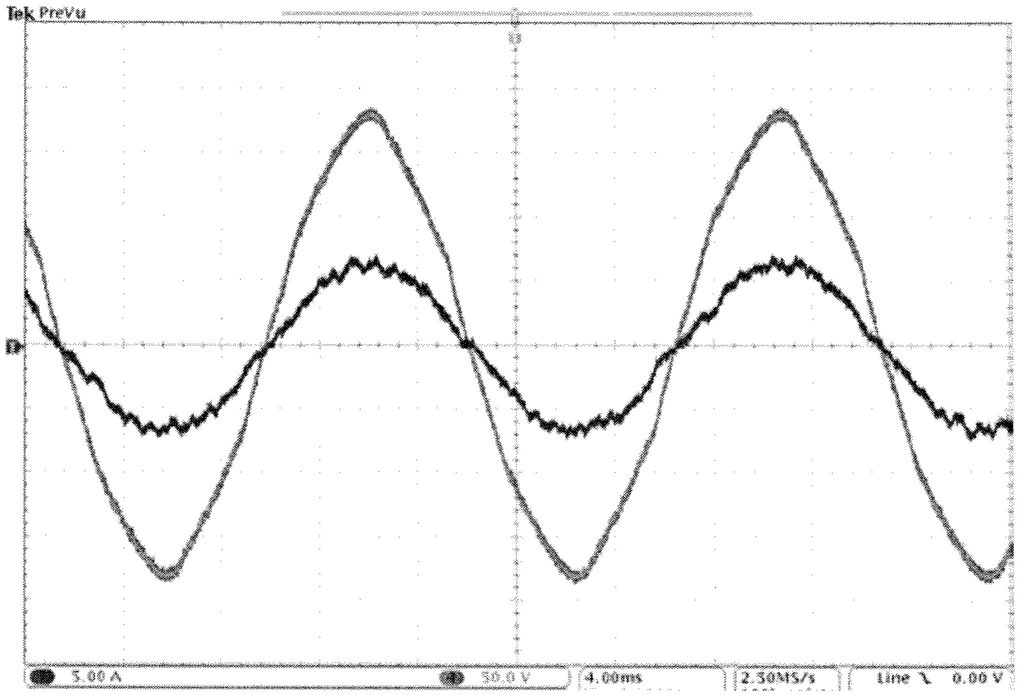


Figure 15. Grid voltage and current waveforms of phase *a*.

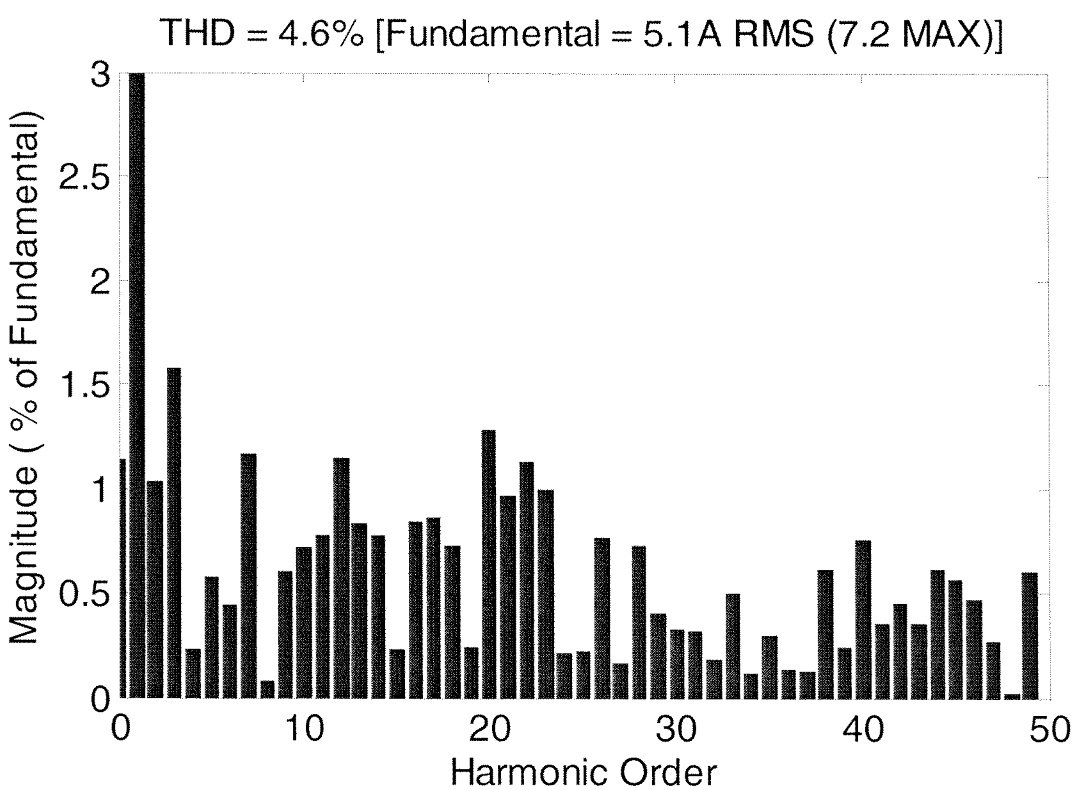


Figure 16. THD of the grid current.

The efficiency of the three-phase 11-level inverter is also evaluated. The full power rating of the system is 30 kW (10 kW per phase), and the inverter is simulated in Saber under different power levels to estimate the power loss. The efficiency of the multilevel PV inverter is shown in Fig. 17.

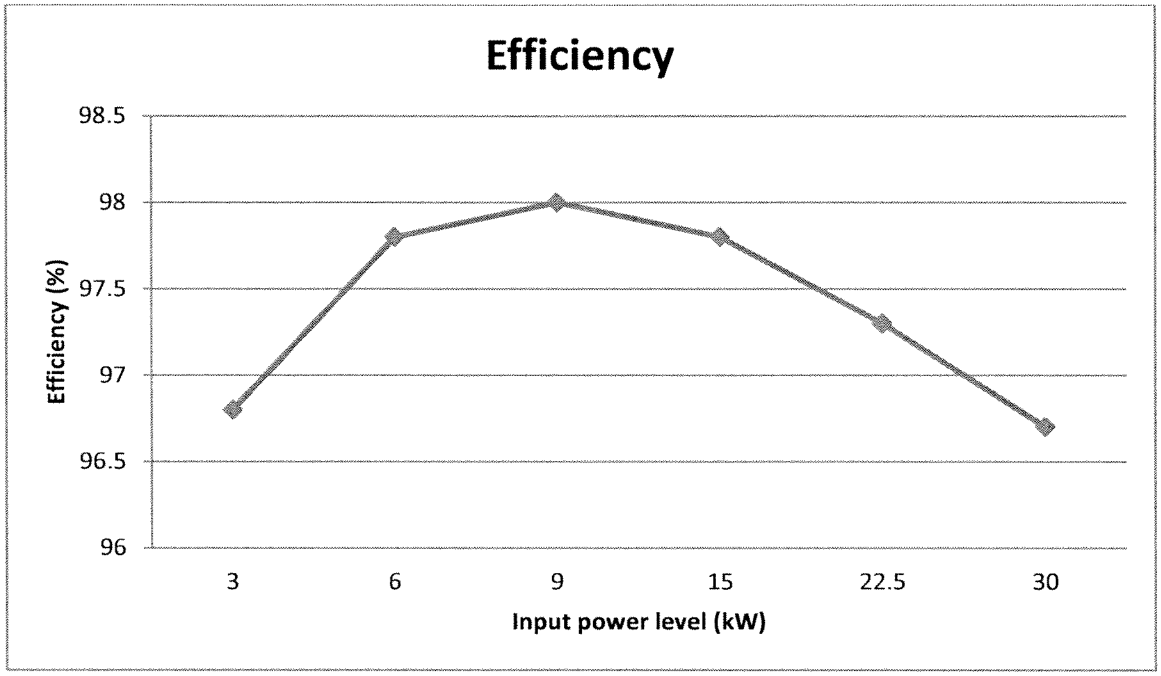


Figure 17. Efficiency of the three-phase 11-level inverter.

**Task 5 - Establish Baseline BOM, Commercialization Strategy and Reliability/Durability Targets and Plan**

Delphi commissioned Johnson Melloh Solutions (JMS), an Indianapolis-based solar energy development company, to prepare a real-world cost comparison between a 200 kW (AC) solar farm utilizing two (2) traditional 100 kW central inverters versus an array of similar scope utilizing thirty (30) cascaded multi-level inverters. The objective was clear that JMS was to go through the typical process of designing and estimating each system as if they were to be built per the interconnection requirements of a utility company. For purposes of this project, JMS chose to present a mock scenario whereby the installation would occur on the southwest corner of Delphi's property located at 2151 Lincoln Road in Kokomo, Indiana.

In the course of analysis, JMS concluded that there is substantial difference in the design of the system, primarily in the wiring. There is absolutely no change to the physical dimensions from one farm to the other, but the cascaded inverter requires more time and material on the AC-side of the system. The same number of 240-watt solar panels (900) was used for each farm. Detailed cost estimates are shown below and include the breakdown of pricing and where the deviation between the two takes place. The cost of the inverters is not included as this is analysis is to reflect the cost considerations beyond the cost of the inverter.

The pricing is largely equivalent between the two farms until data monitoring, DC electrical miscellaneous costs, AC electrical costs, and labor are factored in. The cascaded system has shorter DC runs back to the inverters since the inverters themselves are being landed on the racking immediately adjacent to the panels, resulting in DC wire cost savings. However, it was estimated that the cascaded system will take longer to install on the DC side due to there being 60% more DC connections and thus more cutting and crimping required. The DC labor costs are higher as a result.

The AC wiring and associated labor will be higher as well. It is common-place that the electrical firm sub-contracted to interconnect the system begins work from the combiner boxes and ends at the central tie-in point, be that a transformer or the electrical panel. The AC work costing estimate accounts for AC wiring, AC labor, and trenching associated with getting the conduit from the combiner boxes to the inverter. The nature of the cascaded system results in the exchange of DC wiring runs for AC wiring runs. The AC runs in the cascaded system will require approximately 400% more in material and labor costs as a result. This price includes a 700-Amp service panel which will need to be landed prior to entering the transformer which varies over the two-breaker panel needed for the traditional 200 kW system (???). The trenching component can remain largely the same if the AC runs are mounted to the back of the racking and combined in a single conduit from the inverter to the central trench. Similarly to that of the AC wiring, data monitoring wire (CAT5 line) will need to be run back to each inverter from a central router/data switch which can add to the costs as well. JMS assumed that the cascaded inverter does not include wireless data monitoring.

In all, the AC-side of the installation coupled with the increased cost of the monitoring equipment far outweigh the possible savings realized in a lower cost inverter and less DC wiring material.

The Delphi team studied the results provided by JMS and the conclusions that were offered by them. As noted in the study, the most significant difference between the central inverter and multi-level inverter architectures is with the installation requirements on both the DC and AC side of the inverter. There was no change to the physical dimensions of the installed field, but the cascaded inverter installation requires more time and material on the AC-side of the system and more labor on the DC side. This time and material difference is significant. The conclusions reached by JMS are extremely concerning to the Delphi team since any cost advantage derived by the multi-level inverter is more than consumed in the additional cost of installation labor and material.

| **200 kW Ground-Mounted System - 2 X 100kW Central Inverters vs. 30 X 6.6 kW CMLI** | | | | | | |
|---|---|---|---|---|---|---|
| Total Solar Module Power | 216000 | Watts | | | | |
| Total Inverter Power | 200000 | Watts | (200kW for CI, 198 kW for CMLI) | | | |
| Total Power for $/Watt Calculations | 200000 | Watts | | | | |
| | Conventional | | CMLI | | CMLI Penalty | |
| | Cost ($) | $/Watt | Cost ($) | $/Watt | Cost ($) | $/Watt |
| General Conditions/Overhead | | | | | | |
| Project Management | 21600 | 0.108 | 21600 | 0.108 | 0 | 0 |
| Engineering | 10800 | 0.054 | 10800 | 0.054 | 0 | 0 |
| Rental Equipment | 4320 | 0.0216 | 4320 | 0.0216 | 0 | 0 |
| Permits | 2000 | 0.01 | 2000 | 0.01 | 0 | 0 |
| Interconnection Fees | 200 | 0.001 | 200 | 0.001 | 0 | 0 |
| Materials | | 0 | | 0 | 0 | 0 |
| Solar Panels (900 X 240W) | 194400 | 0.972 | 194400 | 0.972 | 0 | 0 |
| Racking System | 103680 | 0.5184 | 103680 | 0.5184 | 0 | 0 |
| Inverters | not incl. | not incl. | not incl. | not incl. | not incl. | not incl. |
| Data Monitoring | 2160 | 0.0108 | 10260 | 0.0513 | 8100 | 0.0405 |
| DC Elec. Misc | 15120 | 0.0756 | 6480 | 0.0324 | -8640 | -0.0432 |
| | | 0 | | 0 | 0 | 0 |
| Sales Tax | not incl. | not incl. | not incl. | not incl. | not incl. | not incl. |
| | | 0 | | 0 | 0 | 0 |
| Subcontractors | | 0 | | 0 | 0 | 0 |
| DC Labor | 32400 | 0.162 | 38880 | 0.1944 | 6480 | 0.0324 |
| AC Work | 54000 | 0.27 | 118800 | 0.594 | 64800 | 0.324 |
| | | 0 | | 0 | 0 | 0 |
| Miscellaneous | | 0 | | 0 | 0 | 0 |
| Contingency | 21600 | 0.108 | 21600 | 0.108 | 0 | 0 |
| | | 0 | | 0 | 0 | 0 |
| Sub Total | 462280 | 2.3114 | 533020 | 2.6651 | 70740 | 0.3537 |

### *Final Status Summary*

The team, led by Delphi, continued to analyze the cascaded multilevel system architecture options and cost trade-offs during team meetings and in discussions with JMS as described above. Additionally, Delphi undertook separate discussions with Shoals Technologies (a large PV system engineering and manufacturing firm located in Tennessee) discussing the multi-level architecture requirements and costs. Like JMS, Shoals noted the negative impact on the labor and material required for installation.

In addition to the installation cost impacts discussed, Delphi has been working on the mechanical design of the inverter and the required thermal dissipation needs. As was described above, the initial estimate of the mechanical design utilized $D^2$ FETs mounted directly to the circuit board and thermally connected to the housing through thermal circuit board vias. After a more detailed analysis of the requirements, it was determined that the inverter would need to utilize transistor devices clamped to the inverter heat sink or housing. This approach is more thermally efficient than the thermal via approach but more expensive and less compact. As a result, the inverter cost for both material and assembly labor increased over the initial estimates. Delphi estimates the impact near 2.4 cents per watt on the 6.6kW inverter design. In the final analysis, Delphi concluded that the cascaded inverter architecture did not offer enough or potentially any cost advantage over a central inverter on a per Watt basis. Additionally, the installation cost for the multi-level approach was significantly more. The commercial risk to Delphi was significant since the mature central inverter architecture offered likely installation and unit cost advantages. Delphi presented these results to the DOE with the recommendation to terminate the project at the end of Budget Period 1.

### *Patents*

One Delphi-only patent application was submitted under this project. The patent title is " Cascaded Multilevel Inverter Control for Solar Panels." The requirement for patent certification required by the DOE for this project will be uploaded separately to the DOE PMC site.

### *Publications/Presentations*

As has been reported and summarized in prior quarterly reports, UTK published and presented two papers associated with this project.

B. Xiao, K. Shen, J. Mei, F. Filho, L. M. Tolbert, "Control of Cascaded H-Bridge Multilevel Inverter with Individual MPPT for Grid-Connected Photovoltaic Generators," IEEE Energy Conversion Congress and Exposition, Raleigh, North Carolina, September 15-20, 2012

B. Xiao, L. Hang, C. Riley, L. M. Tolbert, B. Ozpineci, "Three-Phase Modular Cascaded H-Bridge Multilevel Inverter with Individual MPPT for Grid-Connected Photovoltaic Systems," IEEE Applied Power Electronics Conference and Exposition, Long Beach, California, March 17-21, 2013

These papers have been uploaded to http://www.osti.gov/elink-2413 DOE site.