Modular Electric Generator
Rapid Deployment DC Microgrid

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***Abstract*—The development of a rapidly deployable modular electric generator based on plug-in hybrid vehicle DC architectures provides a highly reliable DC microgrid for use in applications with unstable infrastructure or highly sensitive loads. The result is the commercial production of early stage prototype units built by Schneider Electric with onboard energy storage, combustion generator and rapid interconnects for loads, renewable energy and grid connection.**

***Index Terms*—DC, microgrid, modular electric generator, distributed renewable energy resources, distributed energy, FREEDM Systems Center**

I. INTRODUCTION

The development of electric drive vehicles (EVs) has been ongoing since the late 1800's. However, unlike the electric utility grid this development has been purely kept as direct current (DC) in storage, distribution and control. These DC based electric power systems have rapidly developed in the past 20 years as a large number of new hybrid (HEV), plug-in hybrid (PHEV), and battery electric vehicles (BEV) have been introduced.

The Modular Energy Generator (MEG) was inspired by recovery efforts in Haiti following a devastating earthquake in 2010. The possibility of high mobility and reliability afforded by a plug-in hybrid electric vehicle with bidirectional vehicle charging triggered the MEG concept. Such a vehicle can be connected to the electric utility grid quickly and easily or in the absence of a usable electric grid, operate in islanded mode much like a PHEV operating strictly on fossil fuel in the absence of a charging station.

II. DEVELOPMENT PROCESS

From the notion of a PHEV based DC Microgrid a standard vehicle development process was implemented where the conventional design drive cycle was replaced with a typical electrical load profile.

A. Architecture Development

One of the greatest challenge facing development of microgrids is the custom design and engineering required for each installation. This level of design represents a substantial proportion of the overall cost of a microgrid deployment. A significant goal of this program was to develop a standard microgrid building block which can be used alone or in conjunction with others to handle scale. One of the founding premises in the automotive industry is the mass production of well-engineered systems which fits this design goal well.

The modular and mass produced building block concept is commonplace in manufacturing with economies of scale and in electrical design such as using Power Electronics Building Blocks (PEBBs) to develop modular power converters. Implementing the modular building block design significantly reduces the monetary cost of microgrid deployment and allows variable size solutions to be custom fit to the target location needs with significantly less front end engineering design work.

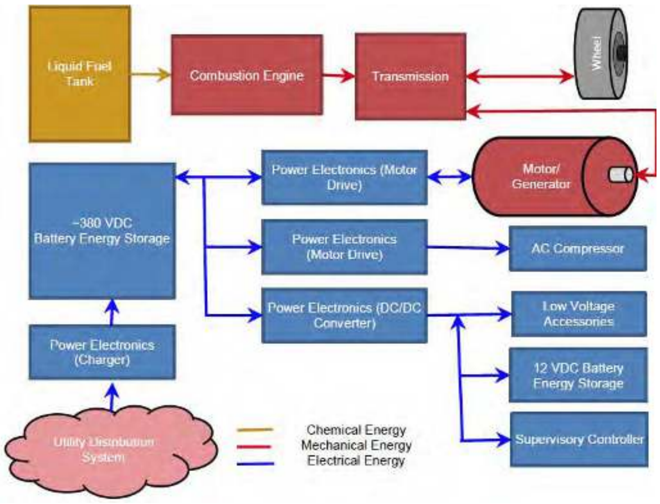

Fig. 1: Typical Plug-in Hybrid Vehicle Architecture

The architecture of a PHEV is DC and highly similar to that of a typical DC microgrid. This architecture includes batteries and loads managed by power electronics as controllers of the power flowing to downstream devices as shown in Fig. 1. This architecture shows the supervisory controller that the vehicle industry has adopted from the widespread use of Supervisory Control and Data Aquisition (SCADA) control for use in complex industrial processes [1]. In the case of PHEVs, communication is fairly standardized using Controller Area Network (CAN) communication protocols while microgrid communications have a mixed set of protocols ranging from wired methodologies like Distributed Network Protocol (DNP) and MQ Telemetry Transport (MQTT) to a host of proprietary and various standards of wireless methodologies.

The MEG concept is based on the architecture shown in Fig. 2. The MEG incorporates similar inputs and outputs as the PHEV shown in Fig. 1 yet adds both DC and AC output panels and a solar array with integrated Maximum Power Point Tracking (MPPT) and removes the mechanical energy output to the vehicle drive train. Beginning with this architecture in mind, the development team traveled through the industry standard vehicle development process beginning with the task of identifying available components, sizing and system modeling.

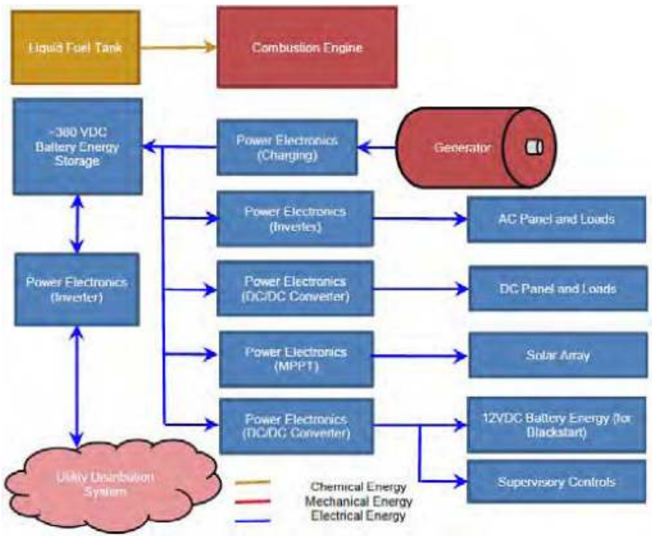

Fig. 2: DC Microgrid Architecture

B. Vehicle Development Process

To handle rapid development while maintaining high quality standards the automotive industry has established intensive design processes designed to take advantage of existing knowledge systematically while identifying and bringing in new knowledge [2]. Well known to the automotive industry, the Vehicle Development Process (VDP) sets the tone and rigor for all product development from the long time-frame complete vehicle redesign to small model year updates. The customer needs assessment is at the core of the vehicle development processes as referenced in Fig. 3. In this case, the developer was the NSF Future Renewable Electric Energy Delivery and Management (FREEDM) Systems Center and the customer was Positive Energies. However it is noted that the ultimate customer is the end user of the MEG.

One of the earliest successes in microgrid development was a group called EarthSpark, who began an effort to develop microgrids in Les Anglais, Haiti [3]. To develop these microgrids, the founder of EarthSpark, Dr. Dan Schnitzer spent years in the region learning the electricity use paterns and habits of villages in Haiti. Dr. Schnitzer was asked to serve in this program to represent the needs of the Haitian customers in the Microgrid Development Process.

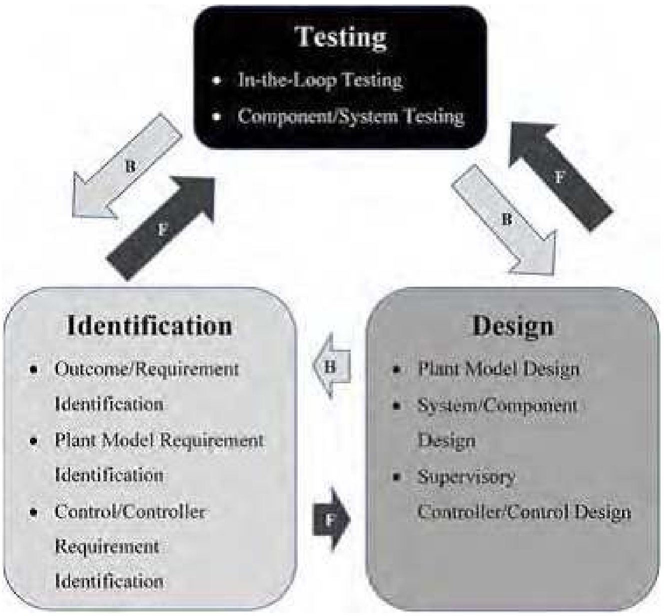

Fig. 3: System Development Information Flow

Stemming from discussions with Dr. Schnitzer, the development team was able to develop a load profile of a hypothetical village of 50 houses with blended ac and DC use. Lighting and other loads that can selectively be supplied by DC such at resistance based loads were included in the DC load profile, while other conventional loads such as conventional fans were included in the ac loads.

TABLE I: Experimental Setup Parameters

Component	MEG System Requirements	
	Requirement	*Numerical Requirement*
Platform	US Manufactured	N/A
Platform	Output Power	50 kW
Platform	Levelized Cost of Energy	>0.16 $/kWh
Engine	Tier 4 Emissions	N/A
Engine	Duty Cycle	24 Hour
Engine	Cycle Life	10 Year Min
Battery	Power	50 kW
Battery	Voltage	380 VDC Nominal
Battery	Temperature Range	-20 to 65°C
Grid Inverter	Power	25-50 kW
Grid Inverter	MEG Side Voltage	380 VDC
Grid Inverter	Grid Side Voltage	480V 3Φ

Table I provides many of the minimum requirements established during the design phase. These minimum requirements were then used to create a design matrix. This design matrix provides a framework to begin development of Matlab Simulink simulations for the model based design approach in conjunction with the VDP. This process is an iterative one where information is fed forward and backward between needs identification, testing, and design [4].

The research team created input files for the established load profile and several likely use cases of solar production. Plant models were created based upon experience from each of the components and simulations provided adequate information to provide the project sponsor (Positive Energies) with input to help determine rough component sizing. The component sizing was then used to evaluate the marketplace and work to understand component availability, volume, and pricing from a variety of likely component manufacturers.

As the unit was being developed, additional load profiles were constructed and simulated based on additional demands for the MEG units. These loads include the use for airport runway lighting, a convention center, and an off-grid resort in a remote location. Fig. 4 shows the final resulting architecture which is fairly similar to the originally developed one although several different architectures were considered during the design phase.

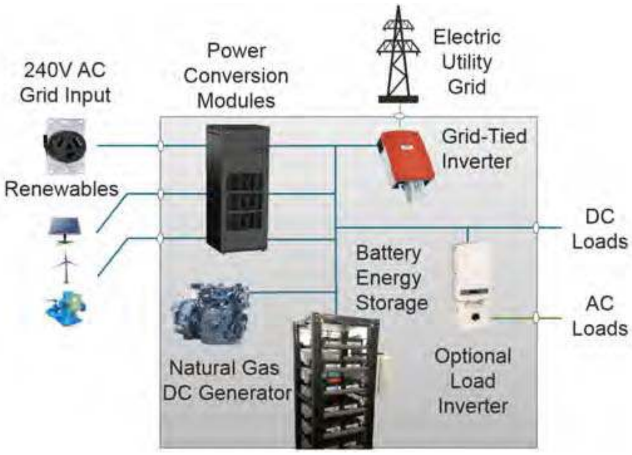

Fig. 4: Final MEG Architecture

C. Battery Development

Following system modeling a final lithium based battery selection was determined which provided a 4C capacity and favorable life cycle financial results. A custom battery management system (BMS) was developed which serves as a mediator with each modules cell management system and as a result allowed the developers to avoid proprietary software overriding the performance of the system. A single rack of 13 battery modules was built to develop the in-house developed BMS and to test overall pack performance. This pack design has a rated nominal capacity of 14.3 kilowatt-hours (kWh) under standard testing conditions. During testing, performance exceeded modeling results with greater power and energy capacity and the battery system provided lower heat rejection than expected. To some degree, this is expected early in the life of a battery module. Individual cells were also tested on an Arbin cycler for lifetime validation with results similarly exceeding manufacturer performance specifications.

Due to the excellent power and thermal performance, the final peak power design from the battery pack was increased to 57 kilowatts (kW) for short term high power delivery. This allowed the burden of high power draw from the DC bus to be significantly reduced from other components such as the grid side power electronics and the internal combustion engine and generator system.

D. Internal Combustion Engine and Generator Development

The original internal combustion engine and generator design was to use an automotive grade hybrid electric vehicle driver train system due to the low cost and high production volumes. However the supply chains investigated require high volume purchase commitments even for prototype systems and automotive manufacturers were reluctant to take on the warranty risk of their components being used outside of their original design environments. Other investigations turned up very few DC internal combustion engines and generators and the few that are available carry a high price per kW.

During the design process, the engine choice was also found to bear a high burden due to the unknown fuel availability in different regions where the MEG may be in use. For emissions reductions and lower overall life-cycle cost, the use of 10 kW natural gas DC generators were selected. It should be noted that based on system modeling, the generators are typically not cycled often as their overall cost is typically similar to grid provided energy. As a result, the natural gas internal combustion engine and generator is treated as a redundancy to provide power in cases where grid power is otherwise unavailable or inadequate.

The inclusion of an internal combustion engine and generator provides long term, low energy production to be supplemented. This can be viewed as a PHEV with a fully electric drive train and a range extension system. Although the MEG is designed to operate primarily off of the electric grid, renewable energy input and battery array, energy extension can be granted or supplemented during prolonged grid or renewable energy shortages.

E. Power Electronics Selections

Although high efficiency power electronics are beginning to make headway in the marketplace due to recent commercialization of new wide bandgap solutions, few of these have made their way into widely available power electronics for low volume purchasing. As a result, the overall power electronics solutions used in the early MEG designs is intended to be revised periodically as new solutions become more widely available.

A high efficiency and modular power converter technology is used to take a variety of inputs ranging in AC and DC inputs with variable frequency and voltage levels. The single design of power converters that can take AC and DC power input allow for spare parts inventory to be minimized, and flexibility in design to be maximized.

III. PROTOTYPE BUILD

A. Laboratory Prototype

The final architecture was first built in a laboratory setting with integrated solar arrays and electric motor loads. Fig. 4 shows the architecture used in this prototype and also in the final factory built units. This unit allowed for proof of concept and final specifications to be developed and supervisory controls to be further developed. The laboratory test unit is still used for troubleshooting and software development.

Additionally, this base laboratory platform is able to perform a variety of both grid tied and standalone microgrid testing in the FREEDM Systems Center laboratory. Having a standalone DC microgrid opens many doors to additional prototype and control algorithm testing which is helping North Carolina State University researchers continue to develop innovative microgrid solutions. Example testing opportunities that have been explored with the MEG prototype include:

- Battery control optimization
- Transition from islanded to grid-connected mode testing
- AC to DC load conversion
- Microgrid dynamic load experimentation

B. Factory Build

Positive Energies partnered with Schneider Electric to construct the factory built solution and overall housing. The original design for the housing of the units is a small shipping container; however a less expensive, more robust solution was developed through the Schneider relationship.

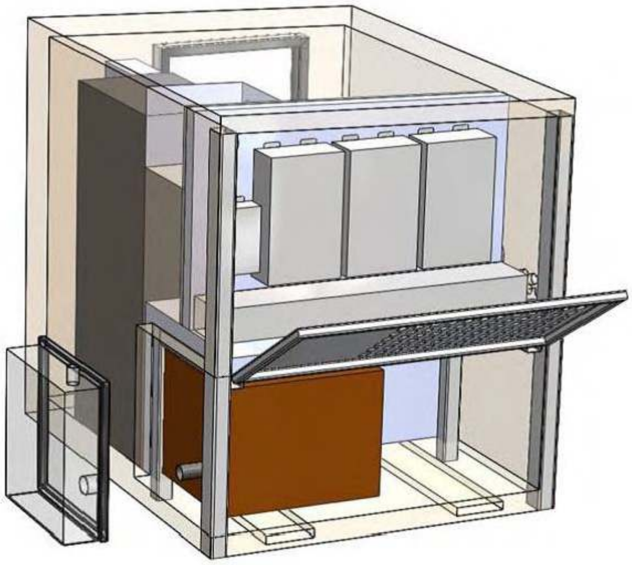

Fig. 5: MEG Prototype Developed by Positive Energies and Built by Schneider Electric

Fig. 5 shows the conceptual rendering of the factory built units. The boxes visible in this view are the external disconnects and wire tray for external connections to up to four renewable energy inputs, DC output, and grid input. The initial bidirectional power flow was not built into this generation of the MEG due to a lack of reliable bidirectional power flow solutions. This is a key area of development for the FREEDM Systems Center, and provides opportunities for future industrial partnerships for the center. The unit on the bottom of the MEG shown in brown is the 10kW natural gas genset. The separate cover to the left is air intake and exhaust for the unit. This system is designed similarly to the slide out trays of rear engine transit buses for easy maintenance.

The high power available from the battery units allowed the final design of the MEG to include a three rack battery solution as shown in Fig. 6. This three rack solution increases the total number of modules in the three strings to 39 with overall power of the MEG to 170kW instantaneous and nominal energy of 42.9 kWh.

Fig. 6: MEG Factory Build Battery Racks

Fig. 6 shows the view from the maintenance entrance to the MEG. Only fully trained personnel are intended to enter

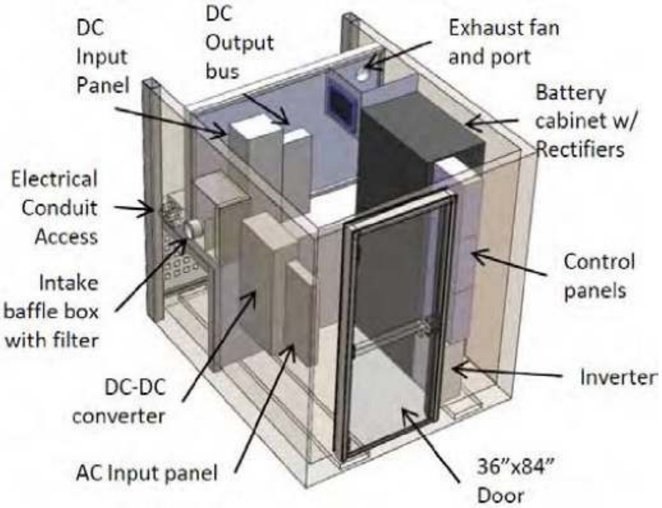

Fig. 7: MEG Protype Built by Schneider Electric with component labeling

the MEG unit where batteries, power electronics, AC input panel, DC input panel, and supervisory controls are housed. The unit has a 36 inch wide doorway to allow for easy removal of equipment and replacement. The unit also houses a fan and exhaust port to maintain airflow and temperature control.

Fig. 8: The MEG was designed to fit four units in a single shipping container

The modular design of the MEG enclosure allows for four units to fit tightly within a standard shipping container as shown in Fig. 8. This design is important in the cost effective pursuit of the MEG project to minimize transportation cost. The shipping container design allows this rugged microgrid to be manufactured in a centralized location such as a Schneider Electric facility. Centralized manufacturing and testing allows for build cost to be minimized, then the fully assembled and tested units can be shipped by truck, train, and boat to locations around the world. Upon arrive the individual units are removed from the shipping container, connected to the grid, load and distributed renewable energy resource, and the DC microgrid is up and running.

An initial build of four MEG units was completed by Schneider Electric for Positive Energies in the summer and Fall of 2016 and has now passed factory acceptance. These units are currently being used for field testing and evaluation as of May 2017.

IV. CONCLUSION

The development of the MEG units has been successful in producing a series of prototype units that provide a highly robust and easily deployable modular energy generator at a relatively low cost. It is expected that future units will cost significantly less and be improved based on the performance findings of the first four units. The vehicle development process provided a clear and thorough development cycle in conjunction with the development partner Positive Energies.

The Modular Energy Generator developed by FREEDM Systems Center, Positive Energies and built by Schneider Electric provides a significant advancement in the cost and deployability of DC microgrids and overcoming the front end design overhead. Continued improvement and next generation development of the Modular Energy Generator platform will continue to refine and adapt the current design as new technologies are developed and control algorithms are written.

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