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Development of a Versatile Plug-In Auxiliary Power System for use in Medium and Heavy Duty Service Vehicles

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Abstract

Southern California Edison (SCE) is an electric utility focused on improving vehicle fleet efficiency to reduce emissions and fuel consumption with vehicle and equipment electrification. SCE played a major role in the design and development of an advanced chemistry versatile plug-in auxiliary power system (VPAPS) with the Electric Power Research Institute (EPRI, Palo Alto, California) and US Hybrid Corporation (Torrance, California). VPAPS is designed to provide up to eight hours of emissions-free electric and hydraulic power for utility service vehicles and equipment using an advanced lithium-ion battery. The system is designed to be modular, and it integrates with existing fleet vehicles through two separate skids: a power electronics skid and a hydraulics skid. It provides 120 volt AC service for power tools and machines, power for hydraulic circuits, and it powers the 12 volt loads of the standard vehicle chassis. VPAPS charges through a commonly used 120V/15A circuit in approximately four hours. The system is designed to operate under rigorous field conditions to support activities that help provide clean and efficient power to SCE customers.

Keywords: Auxiliary, Plug-in, Generator, Lithium-Ion, Hydraulic

1 Introduction

Southern California Edison (SCE) is an electric utility servicing 50,000 square miles in Southern and Central California. SCE operates a fleet of over 6,000 assets ranging from passenger sedans to heavy duty fleet trucks of Gross Vehicle Weight Rating (GVWR) over 15,000 kg (33,069 lb). SCE has a strategy of employing hybrid-electric and all electric vehicles including medium and heavy duty trucks to help improve fuel economy and reduce emissions within the fleet. The Electric Vehicle Technical Center (EVTC) is a testing and evaluation facility within the Advanced Technology (AT) organization of SCE, and has a history of evaluating hybrid/electric technology for the SCE fleet and SCE customers. The EVTC creates testing procedures and methods, and studies performance, efficiency and grid impact from the latest technology around alternative fuels including electricity, energy storage, and plug-in hybrid/electric vehicles. The EVTC conducts various charger, energy storage, and performance testing of all advanced technology vehicles and equipment before they are deployed into the fleet.

The EVTC is actively investigating auxiliary power systems to help SCE reach efficiency goals within the fleet. The evaluations provide a gateway to adopting advanced technology and assist with the acquisition of new vehicles and equipment through SCE's Transportation Services Department (TSD).

1.1 Current Field Assessment Techniques, Equipment and Testing Procedure Summary

The EVTC believes that the fuel economy and emissions generated during stationary operations of vocational equipment during field service can create more of an environmental impact than driving to and from work sites, based on previous analysis and evaluation in the utility fleet. The work performed in the field requires significant time on site in comparison to driving time, using power tools that are either separate or attached to the work vehicle. These tools may be driven either by the propulsion engine or portable gasoline or diesel generators. Many medium and heavy duty truck manufacturers are developing technology to help save fuel and reduce emissions through electrification of vocational equipment, rather than systems which include propulsion assistance to reduce cost for utility fleets, but they have not supplied with removable systems with advanced lithium-ion batteries.

SCE line crews rely on vocational equipment to provide electrical and hydraulic power to maintain the power distribution infrastructure. The EVTC works closely with chassis outfitters, and manufacturers in evaluating advanced technology, including mechanical and electrical properties, with defined procedures developed to replicate field service duty. The evaluations help determine whether the new technology provides comparable performance to existing machines, whether it is safe and reliable, how much energy and emissions it saves, and how much noise is reduced.

1.1.1 Vehicle Vocational Equipment

The EVTC testing procedures include evaluations of vehicle auxiliary equipment function in operations frequently completed in the service field. Vehicles equipped with hydraulic circuits can distribute hydraulic power to either aerial lifts with personnel-carrying buckets, digger derricks, and tool circuits. The procedure creates a ratio of gasoline or diesel consumed per number of complete operation (work) cycles. Hydraulic tool circuits are evaluated at 19-38 lpm (5-10 gpm) at upwards of 13.7 MPa (2000 psi) for an extended period of time, while also capturing gasoline/diesel consumed per unit time of operation. A common tool used in the hydraulic tool circuit as an example is the hydraulically operated well water pump (WWP), which is used to remove water from trenches and underground chambers within SCE's service district. The EVTC tests the WWP with a test stand designed to replicate an average well of 3.0 m (10 ft) head. Performance is measured with hydraulic fluid pressure and flow, as well as the ability to operate consistently in the test stand.

1.1.2 Engine Electric Auxiliary Power Generators

The EVTC testing procedures also evaluate gasoline and diesel auxiliary power generators (APG) in order to compare advanced technology to conventional. These APGs may either be portable engine-driven units, or PTO generators driven off the main chassis engine. These electrical APGs provide power to tools used in the field, and in some cases are coupled to existing vehicle harnesses to distribute AC power to electrical outlets built in to the vehicles. In testing, the APGs are subject to loading using resistive and inductive load banks, along with actual field equipment like the electric version of the well water pump (eWWP), which can draw up to 1 kW of electrical load. Each loading condition spans the overall output electrical capacity of the APG, with varying power factors. The EVTC measures fuel consumption and emissions where applicable with the evaluation of APGs.

1.1.3 Electric Storage Auxiliary Power Units

Electric Storage APUs provide electrical power stored from the electric grid (or from an engine) in their battery energy storage systems through an AC inverter. In addition, these units can rely on electric power take off units (ePTO) to run a hydraulic pump and power hydraulic equipment. By installing power electronics meters, fuel flow metering, and emissions testing equipment (if applicable), the EVTC can test overall system efficiency and performance, combined with output electrical power quality and recharge performance. The result provides overall fuel savings estimates when deployed into service.

1.1.4 Cabin Loads

Service vehicles are equipped with radios, IT equipment, and safety lights that require 12 volt chassis power. The EVTC testing procedures investigate total 12 volt loads during vehicle

operation, while the vehicle is off, and when charging when applicable.
Cabin comfort and effectiveness of auxiliary air conditioning systems is also measured.

2 Design

SCE understands the need for portable energy storage that is fuelled from clean grid energy. The Versatile Plug-in Auxiliary Power System (VPAPS) was developed, along with EPRI and US Hybrid, to provide emissions-free hydraulic and electrical support for existing vehicle vocational operations. The modular VPAPS system unit is moveable from vehicle to vehicle, and designed in two separate units: a power electronics skid to provide electrical power and controls, and a hydraulic skid to provide hydraulic power for tools.

2.1 Performance Requirements

Based on requirements set forth by SCE's fleet Transportation Services Department and from the field service assessment, the EVTC has developed a baseline requirements list to define the functionality and operation of the VPAPS. The system is designed to provide a similar level of function to existing vehicles, including electric and hydraulic power output.

2.1.1 Electrical Output

The unit distributes electricity into two banks, up to a total of 4.4 kW of 120 V power. Vehicles with existing APG systems are known to tie all electrical outlets of the vehicle into a common harness that is connected to the energy source (generator). The VPAPS includes a second NEMA L5-30R connector to adapt to existing vehicle harnesses.
The VPAPS is designed to deliver up to 150 A to the vehicle's chassis system, to meet existing 12 volt vehicle requirements to power auxiliary cabin safety and effectiveness equipment (radios, lights, computers). The battery management system will allow safe operation until a certain state of charge (SOC), where it will limit output power, and eventually shut off automatically. A series of warning alarms and a display will warn the user before the shut off point occurs during operation.

2.1.2 Charging

The VPAPS is designed to charge through a common 120V-15A outlet in approximately four hours. The battery and electronics management system will maintain battery and power electronics temperature during charge through a ventilation system and controls.

2.1.3 Hydraulic Power

The VPAPS will adapt to an existing vehicle's hydraulic fluid infrastructure, which includes a fluid reservoir and conditioning system (heat exchanger and fan), with manifolds/solenoids to distribute hydraulic fluid. The VPAPS will provide 22 lpm @ 10 MPa (6 gpm @ 1500 psi) and 37 lpm @ 10 MPa (10 gpm @ 1500 psi).

2.1.4 Packaging

The VPAPS unit is designed to be modular, and removable from the service vehicle. The VPAPS main skid can be entirely enclosed into a 1.4 m (length) x 0.7 m (width) x 0.7 m (height) (54" (length) x 24" (width) x 24" (height)) unit. The hydraulic skid can be enclosed in a 0.7 m (length) x 0.7 m (width) x 0.3 m (height) (24" (height) x 24" (width) x 12" (length)). The electronics skid weighs 290.3 kg (640 lb), while the hydraulic skid weighs 69 kg (152 lb), including a temporary hydraulic fluid reservoir and approximately 3 gallons of hydraulic oil. Both skids are designed to be transportable with forklift provisions. Mounting to the vehicle is accomplished through holes on the base of the VPAPS structure. While the total weight is higher than conceived, it should be noted that in order to be moveable, sufficient structure must be included for safety; systems built into the vehicle's structure can be much lighter. Future VPAPS versions will likely include aluminium construction to reduce weight.

2.2 Power Electronics

The primary power electronics skid contains the energy storage, the power management controls, and the user interface. It is able to support service equipment such as eWWP, power tools like drills and cordless battery chargers, and it supports the chassis 12 volt system.

2.2.1 User Interface

The main interface panel of the power electronics skid provides direct access to electrical output, charging, battery SOC and manual selection of hydraulic skid operation and flow control. A labelled image of the VPAPS interface is shown in Figure 2-1.

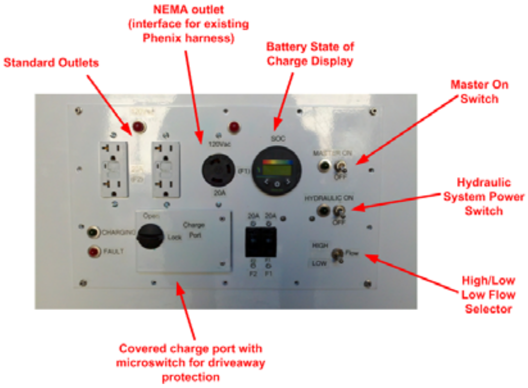

Figure 2-1 VPAPS User Interface

The "master on" switch powers on the unit. Once enabled, the system is ready to operate with power distributed to the electric outlets. Electrical power is distributed to two banks of standard electrical outlets with ground fault interruption, and a NEMA L5-30R outlet, and are both coupled to 20A breakers.
To prevent the user from enabling vehicle operation during charging, a micro switch detects the position of the charge port cover. The signal is coupled to the vehicle harness which disables vehicle movement while plugged in.
The SOC gauge is a control area network (CAN) enabled device which communicates with the battery pack. The display shows battery percentage state of charge and emits an audible alarm for SOC levels below 20% or any temperature dependent point of operation based on the battery performance.
The hydraulic skid is actuated with the flow modulated through two switches. Communication and power to the secondary skid is accomplished through two ports in the rear of the VPAPS, as shown in Figure 2-2. The vehicle interface is completed through a single connector.
The 12 volt output leads tie into an existing vehicle bus to help distribute DC power to vehicle lights, sirens/horns, IT equipment and other typical chassis loads.

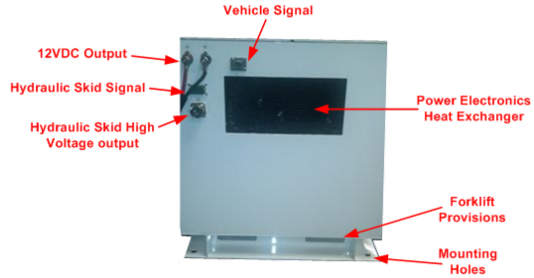

Figure 2-2 VPAPS Rear Panel

2.2.2 Battery

The VPAPS utilizes an advanced chemistry energy storage system. The summary of the specifications is shown in Table 2-1.

Table 2-1 Energy Storage System Specifications

Parameter	**Value**
Chemistry	Li-Ion
Nominal Voltage	360
Number of Cells	96
Mass, kg	90
Thermal Management	Air Cooled
Total Energy, kWh	5.1

It should be noted that the system is versatile enough to work with a range of storage chemistries and parameters, and that there are storage systems at this writing that provide higher energy density, so more work could be performed with the same weight and space.

2.3 Hydraulic Skid

The secondary hydraulic skid is a self-contained structure, consisting of the hydraulic pump and controller. Power and communication to the hydraulic skid is accomplished through two wire harnesses which attach to the rear of the primary power electronics skid (see Figure 2-2). The hydraulic skid can be removed for vehicles without any existing hydraulic infrastructure, but will connect to vehicles already equipped with hydraulic fluid conditioning systems. Should the VPAPS energy level become low, the user can switch back to the existing PTO/ePTO of the vehicle to continue service operations. The hydraulic skid is shown in Figure 2-3.

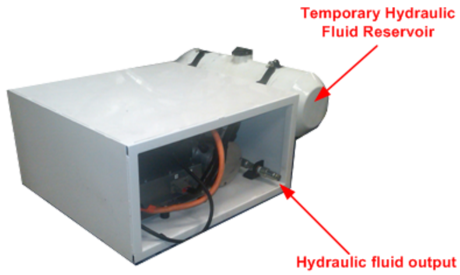

Figure 2-3 VPAPS Hydraulic Skid

2.4 Thermal Management

The VPAPS lithium-ion battery is thermally managed internally with an air circulation system. Air enters and exits through the forklift provisions through the mounting platform for the battery system, as shown in Figure 2-4.

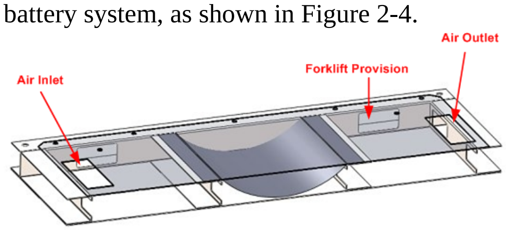

Figure 2-4 VPAPS Battery Air Ducting

The power electronics are thermally managed through a heat exchanger, water pump, and fan. Heat is expelled from the rear of the VPAPS unit, as shown in Figure 2-2.

3 Testing, Evaluation and Comparison

The preliminary VPAPS unit was constructed based on the design requirements developed by the EVTC. The value of a VPAPS system was investigated through previous evaluations of hybrid heavy duty service trucks using EVTC testing procedures, as well as lab and field testing.

3.1 VPAPS Acceptance Testing

The initial acceptance testing of the performance yielded the following results shown in Table 3-1.

Table 3-1 VPAPS Initial Acceptance Testing Results

Criteria	Desired Value	Unit	Tested Value	Notes
Hydraulic Operation				
Low Flow	6	**gpm**	6 gpm	1500psi Test with WWP
High Flow	10	**gpm**	10.3 gpm	Tested with dirt tamper
Electrical Output				
Duplex Bank #1	114-120	**V**	114V	
	20	**A**	18A	Tested with eWWP, Vacuum
NEMA Bank #2	114-120	**V**	114V	
	20	**A**	-	No tool with connector available
DC	12(+1/-0)	**V**	13.4 V	Resistive load bank
	150	**A**	153 A	
Charging				
Input	120	**V**	120 V	
	15	**A**	12.2 A	Meets NEC compliance for continuous operation

3.2 EVTC Laboratory Testing

The preliminary VPAPS unit was tested at the EVTC with resistive load banks, and the eWWP. The entire discharge/charge cycle electric power and total energy input/output has been captured. The results will summarize system efficiency and overall performance.

3.2.1 Electric Well Water Pump

The eWWP was connected to the EVTC test stand and operated after 100% charge. The anticipated load of the eWWP was roughly 1kW, with a power factor (pf) close to 1. With a fully charged pack, the VPAPS should deliver up to an estimated 5 hours of use. The eWWP performance shows a time less than 3 hours and 3 minutes, with close to 3.4 kWh of total energy extracted from the system. Energy was also consumed for power electronics cooling and operation.

After the eWWP operation, the VPAPS had 6.6 kWh of AC energy recharged. The additional energy, beyond the assumed 5% battery overcharge and losses in the charger, is assumed to be consumed by the power electronics and the water cooling system of the inverter and charger.

This inefficient operation of the prototype unit will be further explored and addressed with thermostatically controlled operation. Overall power factor and harmonics of the recharge were good; charger efficiency is still to be measured.

3.2.2 Output Power Quality

The total harmonic distortion (THD) of the VPAPS output power was compared to the 5 kW engine APG tested. The voltage THD of utility systems is generally well controlled at or below 5%. The output voltage THD for the Honda generator was 18.4% and VPAPS was 7.7%, both tested at 2 kW and a power factor of unity. This demonstrates the improvement in power quality over the commonly used generator. Excess distortion is inefficient and can cause sensitive equipment to function improperly or damage it. An example of the wave profile is shown in Figure 3-12 and Figure 3-3. The VPAPS power quality was recorded into two channels, A and B, due to power output limits of the outlets.

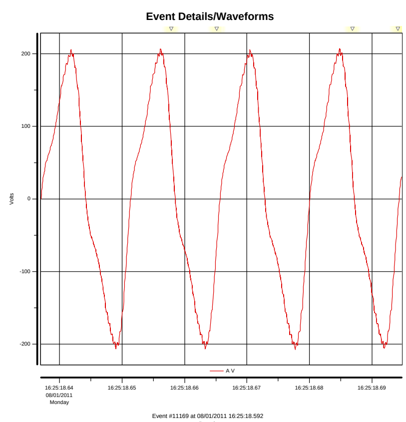

Figure 3-1 APG 5 kW Voltage THD (18.4%, 2 kW, 1 pf)

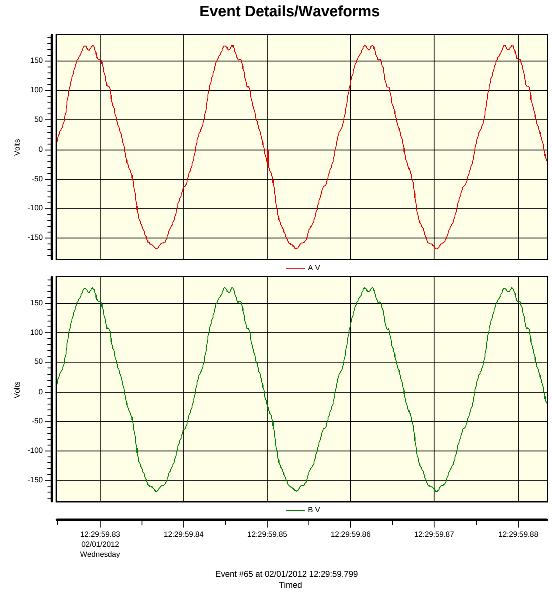

Figure 3-2 VPAPS Voltage THD (7.7%, 2 kW, 1 pf)

3.2.3 Fixed Load Evaluation

The VPAPS unit was connected to resistive load banks and tested at 2.00 kW and 3.65 kW. The 3.65 kW level was selected as the peak tested output of the VPAPS, as the output current is regulated to 80% of the fused limit. In the case of the VPAPS, the limit was 16 A. The closest setting on the load bank was 3.65 kW. The 2.00kW test resulted in delivery of 3.8 kWh in 2 hours of operation, while the 3.65 kW load absorbed 3.6 kWh over 1 hour and 5 minutes.

3.2.4 Fleet Effectiveness Studies

The justification for plug-in battery powered vocational equipment stems mainly from the cost and emissions savings of replacing petroleum fuel with electric fuel.

To compare the VPAPS with a gasoline generator in terms of fuel consumption, a 5 kW engine generator was tested at the EVTC at 2 kW of electrical load. The average fuel consumption was taken for the series of tests, and is shown in Table 3-2 **Error! Reference source not found.**. The similar load was tested on the VPAPS, with a total operation time from 100% charge to shutdown also shown in Table 3-2

Table 3-2 Tested Gallons Saved

Factor	Value	Unit
Average APG 5 kW Fuel Consumption Rate	5.45	**gal/hr**
VPAPS Operation Time under 2 kW load	2	**hr**
Gallons Gasoline Saved	10.90	**gal**

The total (including production and generation) estimated CO_2 emissions from the recharge energy taken after the 2 kW discharge of the VPAPS unit, along with the calculated tailpipe and upstream CO_2 emissions from the APG 2 kW tests is shown in Table 3-3. The total carbon dioxide emissions of the VPAPS unit are estimated to be 3% of the engine unit. The total CO_2 per hour for the VPAPS is estimated at 2.08 pounds, compared to 133 pounds for the engine APG.

Table 3-3 Carbon Dioxide Emissions for two hour test

Factor	Value	Unit
Total tailpipe and upstream CO2 content per gallon gasoline [4]	11.08 (24.42)	kg/gal (lb/gal)
Estimated CO2 content for electricity [5]	630.89	lb/MWh
APG CO2 Emissions	266	lb
VPAPS Charge CO2 Emissions	4.16	lb

4 Conclusion

The prototype VPAPS unit is scheduled for further evaluation using EVTC testing procedures to understand function and energy consumption characteristics of the power electronics and cooling system, to measure power quality and system impact, and to gauge user acceptance. The savings in fuel consumption in the initial unit testing however have provided the EVTC with an understanding of the potential of battery-based energy storage solutions and the value they can provide to the fleet. Assuming four hours of continuous operation per day, the VPAPS unit would save almost 22 gallons and $87 in gasoline ($4 per gallon).

The initial unit will be deployed into the SCE fleet for field evaluations after laboratory testing. During field service, the unit will be subjected to off/on cycling and electrical and hydraulic loads.
The package was designed to fit on existing service vehicles within the fleet. Although it will fit on many service platforms, the first candidate vehicle is a Ford F550 crew cab truck, with utility boxes and storage rack. An alternate test bench includes a removable trailer to attach to the hitch of a utility truck. The VPAPS will be positioned so the user interface is on the passenger side, allowing users to be away from street side traffic. The proposed truck location is shown in Figure 4-1.

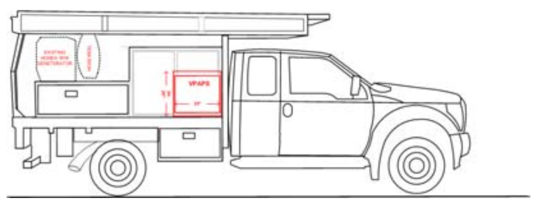

Figure 4-1 Proposed VPAPS Installation Location

Users will be trained on the operation, and the VPAPS' overall functionality.
A full return on investment study will also be completed to investigate the cost and functional impact on the SCE operating fleet. In addition, benefits in worker health (exhaust) and comfort (noise) will be explored.
The VPAPS unit allows SCE to reach efficiency goals. Once the evaluation results are reviewed, the system will begin design iterations to ensure proper optimization of hardware and controls. The data and feedback will help the EVTC enhance the VPAPS in a second generation version, which if successful, could lead to large –scale field deployment.

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References

[1] A.Dalal, J. Smith, "Design and Development of a Plug-in Auxiliary Power Unit for Heavy Duty

Vehicle Applications and Stationary Vocational Equipment", Journal for VPPC 2011 Conference.

[2] GREET Study, Argonne National Laboratory, 1997

[3] R. Bosch GmbH, Automotive Handbook, 5th ed. Stuttgart, Germany, 2000.

[4] www.fueleconomy.gov

[5] California Air Resources Board's Local Government Operations Protocol, Version1.1, May 2010. Appendix Table G.6

Authors

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