SAMINCO
ELECTRIC TRACTION DRIVES

220 kW Traction Drive
for Fuel Cell and Diesel Electric Vehicles

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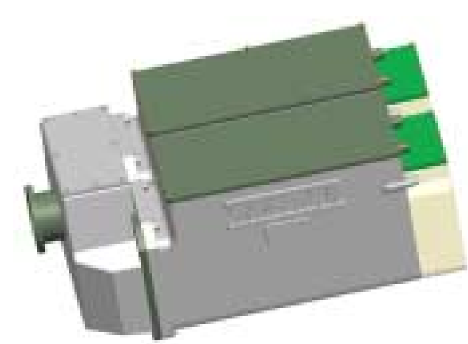
1. ABSTRACT.

The author presents a brief history of the evolution of a 220 kW liquid-cooled DC/AC inverter used to power an asynchronous traction motor for buses and trucks with Fuel Cell or Diesel-Generator Power sources. The present fifth generation inverter, initially designed for 220 kW output, is light and compact and has been found to be capable of continuous 300 kW output with inlet cooling fluid temperatures up to 70 deg C. Designed to operate under harsh environmental conditions, it is capable of functioning while submerged in water, yet can easily be changed out for servicing purposes due to its waterproof power connecting plugs. A sixth generation DC/AC drive, now in development, is based on experience gained over the past decade with traction drives for over 1,000 off-road electric vehicles. This drive comprises a very compact combination inverter/motor and is designed to provide excellent torque response over a 3:1 input voltage range which is particularly useful in enhancing the minimum fuel consumption performance of rotating power sources by adjusting the primary mover's RPM to optimum conditions for a particular power demand.

5th Generation DC to AC Inverter



6th Generation Combined Motor Controller

2. GENERAL.

Over the past 10 years, Saminco has produced approximately one hundred 220 kW DC/AC traction inverters used to test the commercial feasibility of various battery, fuel cell and diesel generator powered buses and trucks.

These inverters had to meet unique design specifications imposed by heavy duty automotive requirements such as compact size, ability to withstand severe environmental operating conditions, compatibility to communicate on SAE J1939 CANBUS, provide automotive industry standard diagnostics and data logging, not cause significant EMI interference and above all provide built-in safety features to minimize electric shock hazards to vehicle operators and maintenance personnel.

3. BUS TRACTION DRIVE EVOLUTION.

In 1989, Saminco supplied a 110 kW DC traction drive chopper and DC/DC battery charger for a 30-foot fuel cell demonstration bus for Ballard of Vancouver, Canada shown in Fig. 1. This unit was air-cooled and used a special lightweight, air-cooled motor developed jointly between Saminco and the Emerson Electric DC motor plant in Chicago. This was the first fuel cell bus ever produced and used an intermediate lead acid battery energy storage system to compensate for fuel cell lag. It had limited service and was retired three years later.

Fig.1: Ballard Phase 1 Bus

In 1991, we supplied liquid-cooled 250 kW versions of this chopper for the three Georgetown University fuel cell buses using air-cooled General Electric DC motors.

Fig 2: Georgetown University Gen I Buses

The second generation Ballard bus was a 40-foot vehicle using a 200 kW brushless motor drive supplied by Kaman and a primary DC/DC up-chopper made by Saminco to compensate for fuel cell load-dependent voltage droop. It was used for test purposes and to demonstrate Ballard's fast-response fuel cell system, which eliminated the intermediate storage battery requirement. This development proved to be so successful that all subsequent Ballard buses were able to provide excellent performance without any form of intermediate energy storage system. Energy regenerated during braking was dissipated in a liquid-cooled resistor and helped maintain the fuel cell's water temperature for proper fuel cell operation.

Fig 3: Ballard Phase 2 Bus

There were six third generation fuel cell buses (Fig 4) using Saminco 200 kW DC/AC liquid-cooled traction inverters with WYE/DELTA switching of the Reuland oil-cooled induction motor's windings to provide 6:1 constant power operation. These inverters were supplied with a primary DC/DC up-chopper to compensate for fuel cell voltage droop under load. Three inverters were supplied for revenue-generating service in Chicago and three were supplied for service in Vancouver. All six buses ran successfully for three years and their operation taught us that we had done a few things right and many things wrong, forming the basis for the next generation of inverters.

Fig 4: Ballard Phase 3 Bus Program

Only five fourth generation liquid-cooled inverters were produced by us for Ballard’s 40 foot demonstration buses, but its design and application was quite novel. First of all, these fourth generation inverters were able to operate directly from the raw uncompensated fuel cell output without benefit of DC/DC up choppers and, again, were used with Reuland oil-cooled induction motors, which were literally “drop-in” replacements for bus diesel engines. Thus, the inverters were not required to operate at constant power over a wide speed range but used standard GM-Allison transmissions and conventional drive trains to provide the wide constant power operating range required in large vehicles. These buses are still in operation and performance has been excellent.

Fig 5: Ballard Phase 4 Bus

Fig 6: Reuland AC Motor Fig 7: Saminco P4 DC to AC Inverter

We used a variation of this design for Allison Transmission Division's (ATD) diesel electric LEAP bus, shown in Fig 8. This inverter was liquid-cooled and used together with a 10,000 RPM, 220 kW liquid-cooled induction motor designed by Dr. Ahmed El Entably of ATD. This motor was coupled directly to the bus drive train via an oil-cooled gearbox and was capable of 3:1 constant power operation at its high-speed range. About half of these inverters were used on vehicles with ATD's unique parallel hybrid EV Drive System about which you will no doubt hear more during this SAE event. We supplied 40 of these inverters to ATD and this program is still underway.

Fig 8: Allison Electric Drive Leap Bus

4. THE M600 DC/AC INVERTER.

Fig 9 shows Saminco's present fifth generation inverter designed to control a 220 kW AC oil-cooled traction motor (Reuland) used on the latest generation of Ballard/EVO 40 ft. fuel cell buses. As in the phase 4 design, the motor is coupled to a mechanical transmission and operated in a similar manner to the previous generation of inverters. Fig 10 shows one of these phase 5 Ballard/EVO buses.

Fig 9: Saminco P5 Inverter

Fig 10: Ballard Phase 5 Bus

Measuring only 585 mm X 470 mm X 215 mm and weighing 58 kg, the P5 liquid-cooled inverter is capable of providing 220 kW continuously with in-coming cooling fluid at 65 deg C when switching at a PWM (Pulse Width Modulated) frequency of 5 kHz. If switched at 2.5 kHz, it is capable of 300 kW output with inlet water up to 70 deg C. The M600 has a 175% momentary overload capability and has been designed to withstand continuous vibration levels of 5g and momentary shock impulses of 40g.

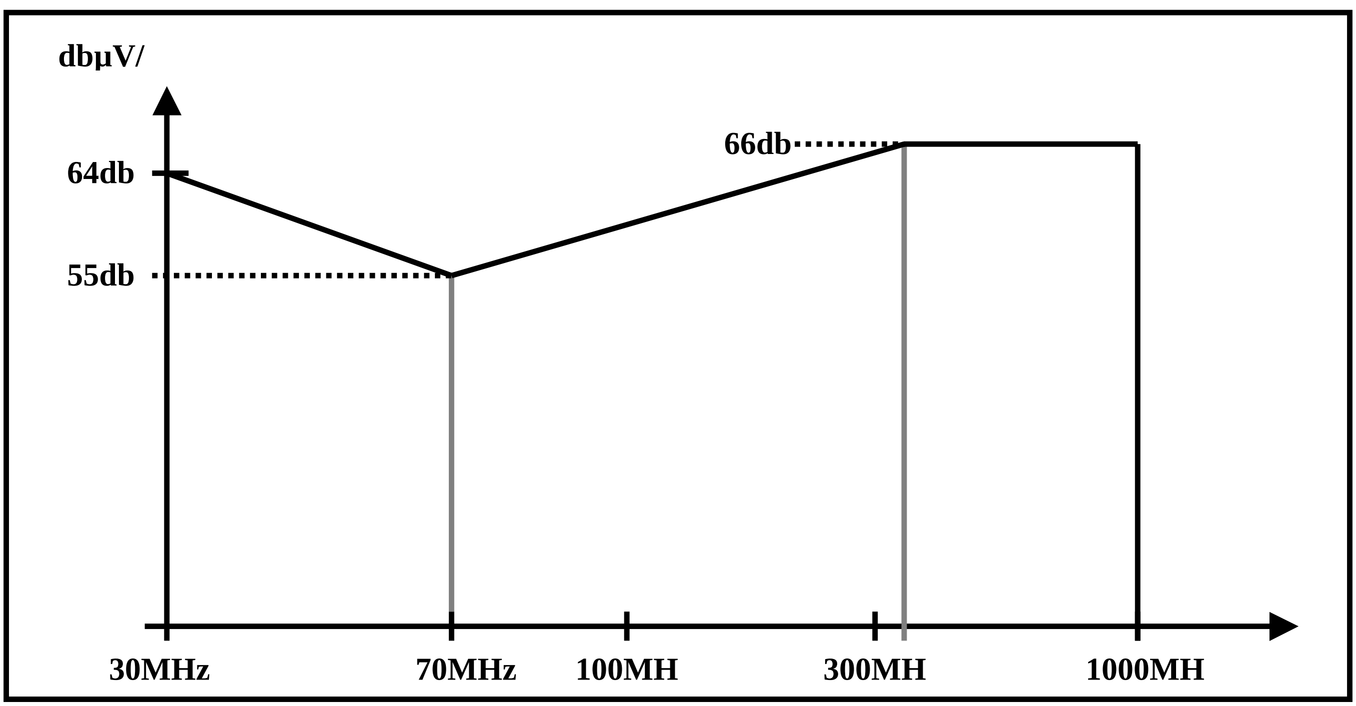
Using specially-designed water-proof power connectors designed and manufactured by RADSOK and AMPHENOL, and water-proof automotive type connectors by Deutsch, this inverter can be interchanged in less than 15 minutes to facilitate rapid servicing yet can function while submerged in water.

As in the phase 4 design, this inverter can operate directly from the raw fuel cell voltage without input voltage stabilization and about 40 units are in the process of being delivered to Ballard at this time.

For safety purposes, this inverter contains a DC-rated 600 Amp power contactor to provide emergency disconnect means from the fuel cell power supply, and an optional separate fail-safe normally closed contactor to discharge the energy-storage capacitors.

4. ELECTRO MAGNETIC INTERFERENCE (EMI)

Saminco has performed extensive EMI testing together with TUV Rhineland to establish compliance to the radiation limits of Automotive Directive 95/54/EC shown in Fig 11. We laid out the location of the DC/AC inverter, traction motor and cabling as used in the 5th generation Ballard/EVO bus (see Fig 12) and had to apply special cable shielding techniques to meet these limits, especially at the lower frequency range.



Radiated Emissions Limit for Electronic Sub-Assemblies at 3m

Fig 12: EMC Compliance Testing at Saminco

This experience has taught us that it is very difficult to meet EMI requirements, especially in the AM broadcast band if separate cabling is used between the motor and inverter.

In addition to the EMI/EMC testing performed at Saminco, all P5 Inverters undergo full load dynamometer testing at Saminco, and prototype units have been subjected to environmental testing at Qualtest test labs in Orlando, Florida.

Fig 13: Ballard Test Dyno / ATD Test Dyno

Fig 14: P5 Inverter after Salt Test

Fig 15: Saminco Load Stand at Qualtest

5. CONVENTIONAL ELECTRIC BUS TRACTION SYSTEM

Fig 16 shows the components used in bus traction drive systems supplied by others for buses powered by fuel cells or diesel generators. They incorporate (1) a DC/DC voltage stabilizer, (2) a separate inductor for the DC/DC chopper, (3) an intermediate energy storage system with related voltage matching devices, (4) DC/AC inverter and (5) the AC traction motor.

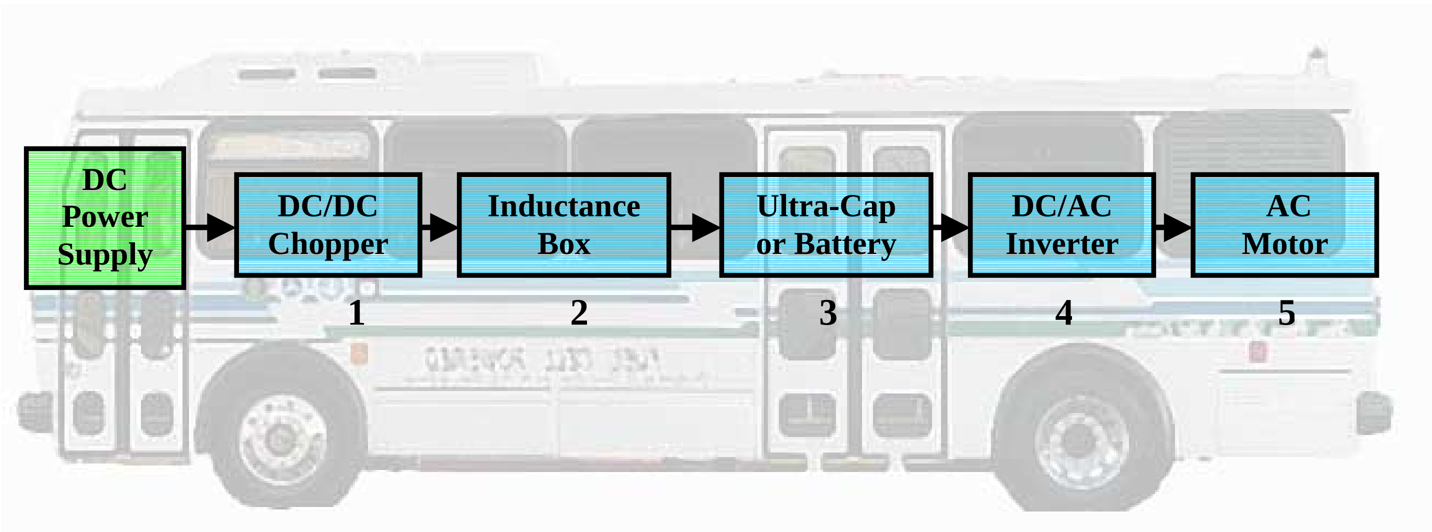


Fig 16: Conventional Electric Bus Traction System

6. INTERMEDIATE ENERGY STORAGE

Intermediate energy storage devices usually consist of batteries, ultra capacitors or flywheels. They are used to allow a reduction in power plant size by providing a source of burst energy required during acceleration and provide an energy sink to allow regenerative braking.

But energy storage units require auxiliary devices for charging or pre-charging and add to weight and system complexity. A proper power control algorithm is difficult to design and if not done correctly, can give rise to system instabilities. The energy storage devices have poor specific energies, of the order of 10 to100 Wh/kg, compared to 12,000 Wh/kg for diesel fuel, and in the case of batteries require considerable maintenance. A substantial portion of the energy savings derived from the use of the smaller power plant is negated by the energy wasted in accelerating the extra mass of the energy storage system.

Then there is the question of cost. It is the goal of us in the electric vehicle business to fashion the simplest, most cost-effective electric traction system possible and it is my view that the goal of having extra accelerating energy available on quick demand is best met by increasing primary power plant size and eliminating the intermediate energy storage system altogether. Regenerated energy is best dissipated in compact, liquid-cooled braking resistors, similar to the existing practice of dissipating vehicle kinetic energy in retarders incorporated in transmissions.

7. DC/DC BOOST CONVERTERS

As mentioned previously, a fuel cell’s output is very load dependent. In the case of a diesel generator power plant, considerable fuel savings can be gained by matching the diesel engine’s speed to power output to achieve minimum fuel consumption.

If the generator consists of a simple, totally-enclosed permanent magnet alternator such as manufactured by Fisher Electric Motor

Technologies of St. Petersburg, Florida, then the output voltage will vary directly with engine RPM.
For both fuel cell and diesel-alternator power plants, voltage fluctuations of up to 2:1 can occur, and in order to allow the DC/AC inverter to provide good torque output over its entire operating range, it is common to interpose a voltage stabilizing booster between the primary power plant and traction motor inverter.

We supplied such a booster for the 6 phase 3 fuel cell buses operated in Chicago and Vancouver during 1997 to 1999, but, as mentioned previously, the newer 5th generation inverter designs do not require such a booster.

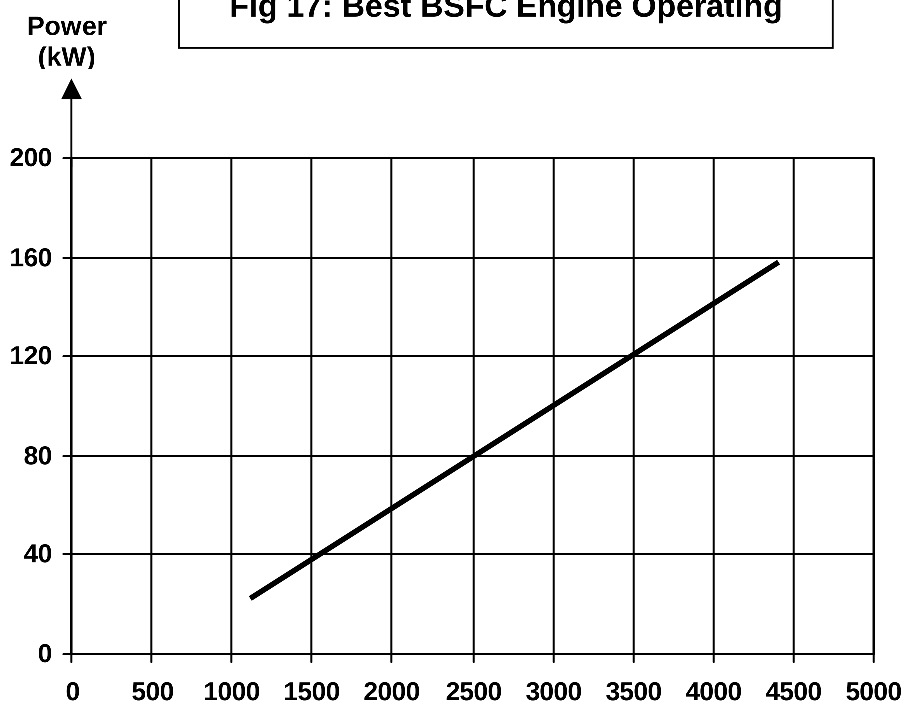
As in the case of energy storage devices, boosters add weight, cost, complexity and, in addition, an unwelcome source of EMI. Their use violates the imperative to supply cost-effective, simple and reliable traction systems for future electric vehicles. Accordingly, this component was eliminated in the phase 4 and phase 5 fuel cell buses and the function of the boost voltage stabilizer was incorporated in the DC/AC inverter.

8. OPTIMUM DIESEL ENGINE OPERATION

The development of a DC/AC inverter capable of providing good torque response over a wide speed range permits the use of a diesel engine generator using a simple, compact, permanent magnet alternator, whose output voltage will vary directly with engine RPM. This gives us the freedom to vary engine RPM to always operate at its minimum fuel consumption point.

Fig 17 shows best BSFC operating characteristics for a 180 kW diesel engine, and suggests that RPM should vary at the rate of 25RPM/kW to always operate at minimum fuel consumption.

Fig 17: Best BSFC Engine Operating



9. SIXTH GENERATION DC/AC INVERTER COMBINED WITH MOTOR (CMC)

Fig 18 shows a liquid-cooled 90 kW combination DC/AC inverter & induction traction motor or CMC for Combination Motor Controller, suitable for propelling a 30 ft. bus for city duty. The unit has a built-in 100 kW peak liquid-cooled braking unit and total mass for the CMC is 170 kg.

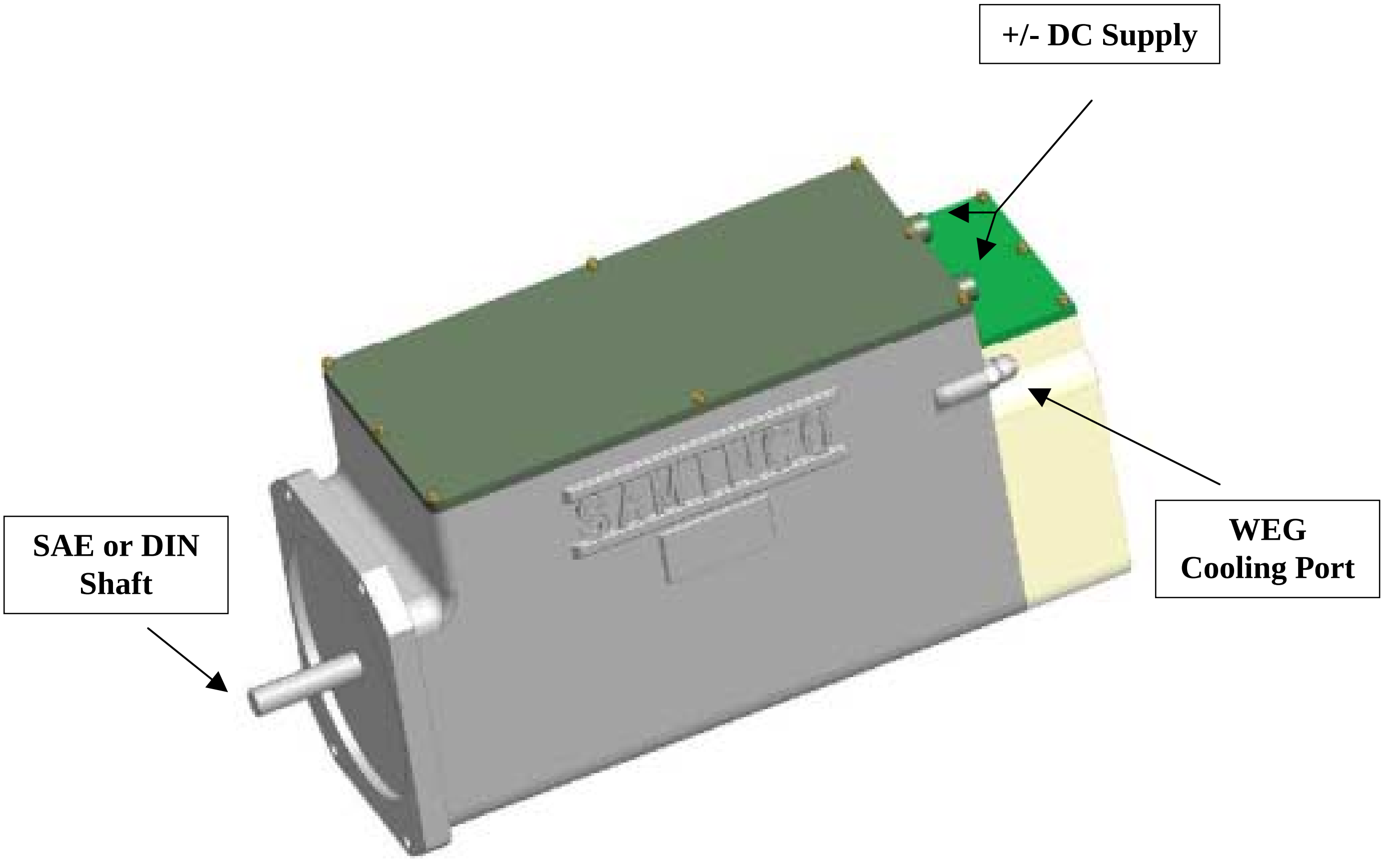


Fig 18: Saminco 90kW CMC Inverter/Motor

Two units can be combined, as shown in Fig. 19, fitted to a summation gear box such as supplied by Flender Corporation of Germany to provide 180 kW continuous power and 270 kW peak output to provide ample power for a 40 ft. bus suitable for city and highway duty. The 180 kW unit is compact and light (estimated mass including gearbox is 440 kg) and can operate directly from an uncompensated fuel cell or diesel generator power source.

Fig 20 shows the application of this unit to a bus propulsion system. The proposed system, used in conjunction with a larger primary source eliminates the DC/DC up-chopper, inductor, intermediate energy storage system and a lot of power cabling. It facilitates EMI suppression, all the way down to the AM band and lends itself to eventual production technology resulting in a low cost electric propulsion system.

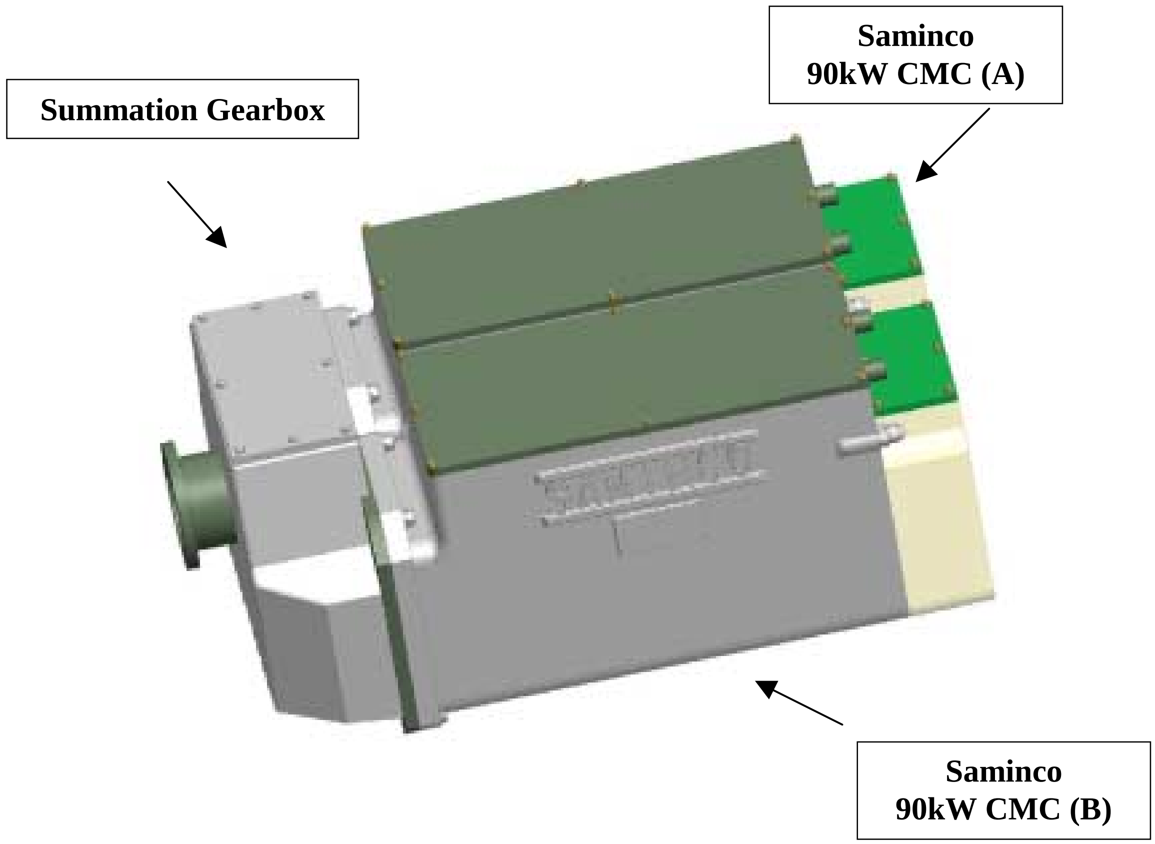


Fig 19: Dual Saminco CMC with Summation Gearbox

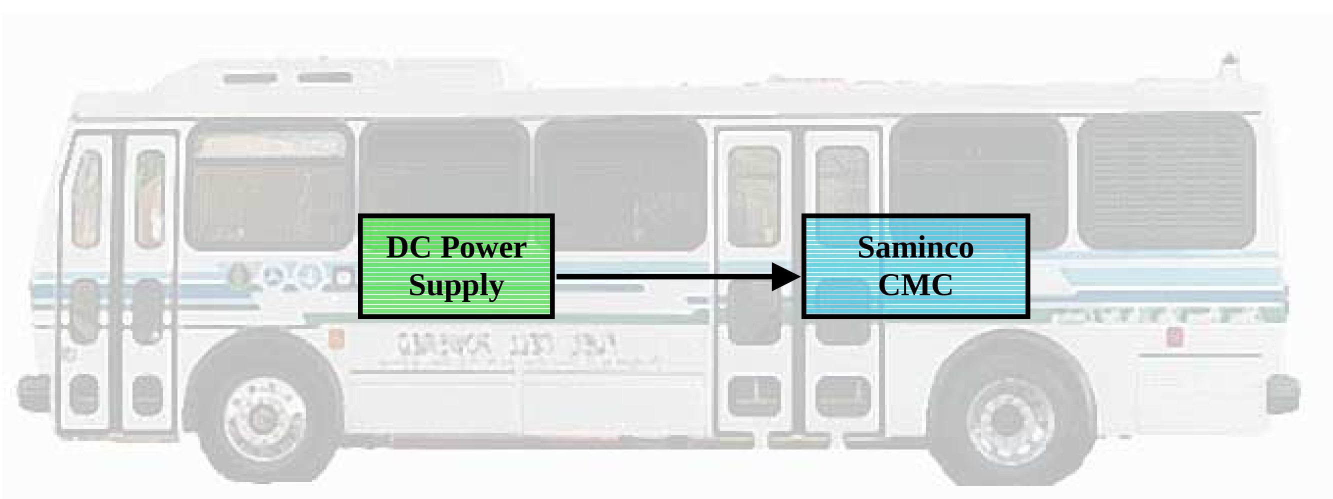


Fig 20: Saminco CMC Bus Propulsion System

10. ACKNOWLEDGEMENTS

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