Resonant Field Modulation
A New Class of Variable Speed Generator

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Background

Raven Technology, LLC (Raven) is seeking industrial partners to participate in the commercialization of a new class of variable speed AC generators (VSG) that produce grid compatible electricity. This new class of generators promises to be less expensive to manufacture than existing variable speed solutions while offering significant design flexibility and operational efficiency, shaft horse power to grid, of better than 90%. This patented technology combines a resonant field excitation technique with a special high frequency alternator to produce precise 60-Hz AC power over a wide speed range without the need for inverters or output filters. Recent work has extended the technology to include a patent for a three-phase machine. The three-phase generator promises to have power densities and construction methods on par with low-cost fixed-speed induction generators. This should allow for a significant price advantage over existing VSG technologies.

Raven has demonstrated the advantages and value of this technology by commercializing the Blackbird™, a 7 kW under hood generator for mobile power applications. The Blackbird™ is being sold as on-board power for fire and emergence vehicles. The generator has found solid acceptance in the market with over 300 units in the field powering lights, electrical equipment and power tools at emergency scenes. The Blackbird™ has succeeded in demonstrating that field modulation is a simple, cost effective technique for converting variable speed shaft power into 60 cycle AC power. As the sole source of AC power on these fire trucks the Blackbird™ has proven the rugged reliability of the basic design and its ability to function in a harsh real world environment. The development of the Blackbird™ has provided a significant knowledge base that should allow for the rapid development of the three phase designs.

Raven is now engaged in contract development work on a 15 kW system for over-the-road refrigeration as well as an 80 kW, 460 VAC direct drive wind turbine generator (April 2010.) Raven is actively looking for additional industrial partners to participate in developing micro-generators for a variety of applications in the 15kW to 250 kW range.

Technical Overview

Raven's variable speed generators are field wound high frequency alternators that use a field modulation technique to produce AC power directly from the rectified output of the alternator. The system controls both output frequency and voltage without the heat, inefficiencies and reliability issues typically associated with inverter technology. This patented alternator is a high efficiency cousin to the automotive alternator. Automotive alternators produce speed independent DC power by using a voltage regulator to adjust the current in the field coil, which in turn controls the output voltage. The Raven approach extends this same control concept by using a patented technique called Resonant Field Excitation to efficiently drive the alternator to produce AC power while still achieving speed independence. The key advantage of this approach is that the high quality wave shaping is done in the low power field circuit, avoiding the cost and inefficiencies of high power switching electronics and filters. The Raven approach offers tremendous design freedom to optimize system efficiency and operational flexibility.

The benefits of this method of power production are:

- Variable shaft speed operation,
- High quality, constant frequency sine wave output power,
- High system efficiency, better than 90%
- Power density equivalent to induction generators,
- Cold start and stand alone operation,
- Rugged, compact electronics,
- Brushless design for low maintenance,
- Elimination of expensive output filters common to inverter technology, and
- Elimination of grid VAR support requirements.

Technical Advantages: Efficiency and Flexibility at a Lower Cost

The fundamental advantage of this technology is that it provides high quality AC power over a wide speed range at a lower cost than current technologies. Current estimates indicate that at moderate production levels in the 80-100 kW range this technology should be able to achieve costs of .14- .18 $/watt.

Variable speed technologies influence the economics of energy conversion in two categories:

- Energy Efficiency, and
- Capital/Life Cycle Costs

Energy Efficiency

The variable speed nature of the Raven system offers both design flexibility and operational flexibility; these can each translate into energy efficiency. In energy conversion systems speed matters, particularly if the load on the system or the power to the prime mover varies. As an example, a generic efficiency curve for gas turbine operating at part load (FIG 1), shows substantial system efficiency change during part load conditions, illustrating that variable speed systems can maintain higher efficiencies. The ability to change the speed of the prime mover in response to part load conditions saves money by improving the over-all system efficiency. Higher efficiencies lead to shorter payback periods and higher revenue over the life of the system. Other energy systems such as wind, hydro, and solar thermal have similar, if not more dramatic, savings available when the speed of the turbine is free to change.

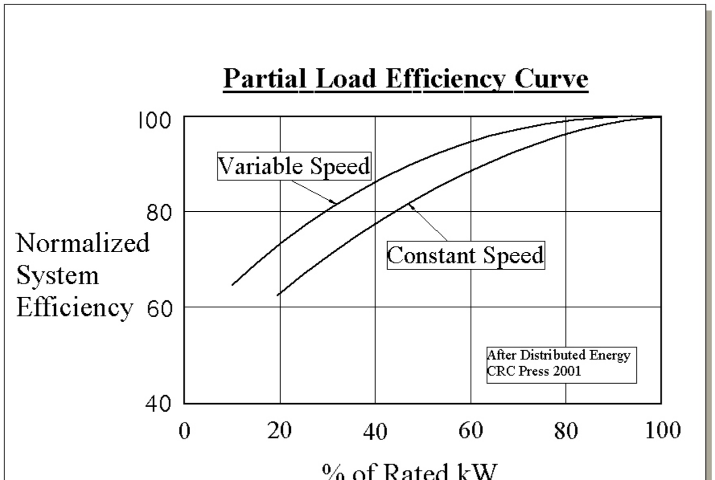


Fig. 1

Capital/Life Cycle Costs
Ravens VSG technology can have a substantial impact on the capital and life cycle cost of an overall generation system. FIG 2, below, shows the system components for two variable speed technologies: the Raven system and an inverter based VSG, a common technology in the variable speed market. Each system offers the flexibility of variable speed operation, but there are substantial differences between the systems that can be understood through a component by component comparison:

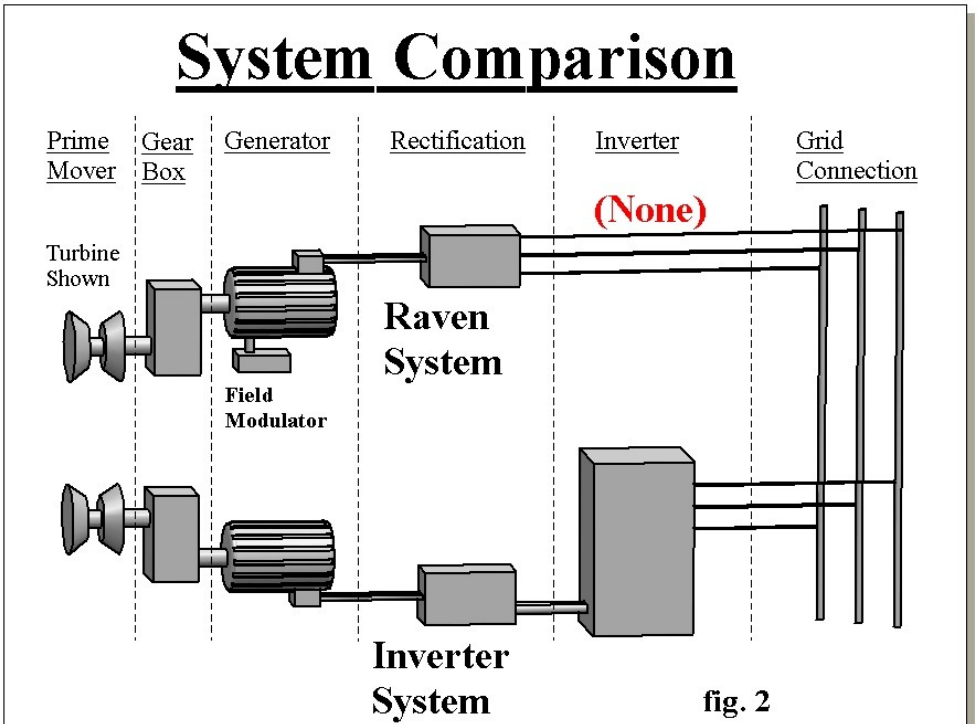


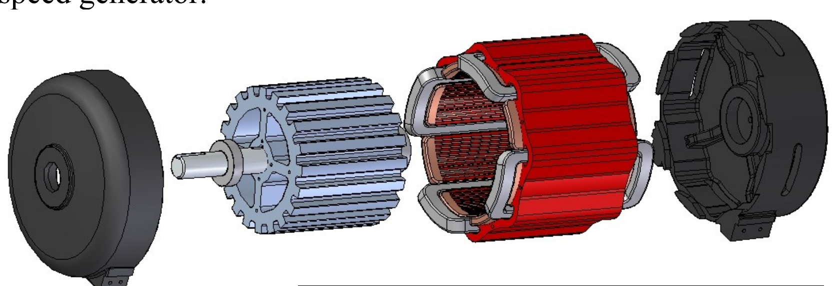
fig. 2

System Comparison

- Prime Mover
  The primary goal of any energy conversion system is to convert energy efficiently from one form into another. All prime movers, be it wind or high speed micro turbines, have power curves that indicate the optimal speed that the device should run at a specific load. The advantage offered by VSG systems is that the speed of the system can be changed to maintain the highest possible efficiency. Improved efficiency goes right to the bottom line as reduced fuel costs for gas turbines or higher energy yield with wind turbines.

- Gear Box
  The ability of VSG systems to break the link between shaft speed and output electrical frequency has had a significant effect in the area of gearing. Traditionally, gearing has been needed in both the low and high speed segments of the market to match the speed of the prime mover to near synchronous speeds of induction and synchronous generators. These gear boxes are expensive and require constant maintenance. The freedom provided by VSG systems allows the designer to choose the most appropriate gear ratio including direct drive. This can allow for simplification, or the complete elimination of the gear box, yielding savings in both the capital and maintenance costs.

- Generator Stage
  The Raven generator is a brushless design which uses a variable reluctance rotor. This means that the rotor is a simple stack of stamped electrical steel laminates without rotor windings, slip rings, brushes or squirrel cage conductors. This design attribute makes the Raven generator **very affordable** with construction features similar to induction generators, the most common and least expensive fixed speed generator.



Raven Variable Reluctance Machine

By comparison, many variable speed systems use permanent magnet (PM) generators which are **expensive** and produce **uncontrolled output voltage** that is proportional to speed requiring an inverter to produce AC power. One advantage of these PM machines is their high power density which makes for a lighter generator. This advantage does come with a significant cost penalty when compared to the Raven system. Estimates in the 80-100 kW range put the cost of the Raven system at about 35% of an equivalent PM machine.

- Rectification
  As shown in the block diagram both the Raven system and the inverter system have a rectification stage. The Raven system uses rugged low cost SCR technology, retaining the advantages of natural commutation and avoiding the losses and stress of high power hard-switching. SCRs are a mature, robust technology available at high power levels. Even less-costly diode- rectification can also be used in specific cases, depending on the details of the application.

- Inverter Stage
  The **Raven system requires no inverter or output filters**. This is a major advantage of Raven's field modulation. The Raven system can be grid compatible directly from the rectification stage.

  By contrast, inverters must switch the full output current at high speeds with hard switching. This requires extensive output filtering and high power transistors. The losses and stresses of this hard switching require extensive thermal management including liquid cooling at higher power levels. The **Raven system entirely eliminates these inverter issues and related expenses**.

- Grid Connect
  Like inverters, the Raven system does not require excitation or VAR support from the grid, a problem common with induction generators. The Raven system can be automatically synchronized with the grid and does not change frequency with load, an issue with synchronous machines.

Obviously the value of these multiple benefits will vary in different applications but to summarize, the following benefits are generally common to all:

1. **Variable speed generation**: allows turbine blades or other power source to operate more efficiently.
2. **Less gearing**: Raven's variable speed generator can be designed to meet a variety of speed ranges, reducing or eliminating the required gearing, which has been a traditional weak spot in the systems.
3. **Reduced mechanical stresses:** Because Raven can control the field strength of the generator we can thereby control the output power level. In wind applications, this control can be used to let the power of a gust flow by reducing the wind load on the blades and torque load on the transmission. Alternately, Raven's variable speed capability can allow the gust energy to accelerate the turbine blades; capturing the gust energy as stored momentum which can then be delivered smoothly to the grid as the gust subsides.
4. **No grid excitation power required:** Raven's system does not require excitation power from the grid, reducing grid transmission requirements and losses.
5. **Stand-alone generation:** Raven's system can provide stand-alone power for loads without grid attachment.
6. **No frequency sag:** Raven's variable speed technology can provide fixed frequency output and, unlike synchronous and induction systems, the frequency does not slow as the system is loaded.

7. **Brushless, field controlled generator:** Low cost variable-reluctance rotor requires no permanent magnets, rotor windings or squirrel cage conductors.
8. **No output inverters:** Low cost and weight. Minimal filtering required. Robust "soft switching" reduces power electronics heat losses and stress.
9. **Eliminating grid surge and flicker:** Raven's variable speed technology can smooth the energy extraction, eliminating power surges and flicker during gusts.

Market Advantages

Raven sees the markets for VSG technology breaking generally into various speed classes based on the type of prime mover.

- **Low speed** – Wind and Hydro energy applications,
- **Moderate speed** – Internal Combustion engines, mobile and stationary,
- **High speed** – Rankine turbines for combined heat and power, geothermal and solar thermal applications, and
- **Very High speed** – Gas Turbine and Micro-turbine gen sets.

Wind Applications

The schematic in FIG 3 shows a typical wind turbine system. The dollar signs highlight the areas where the Raven system can save money, either through first costs, maintenance costs, or efficiency improvement. One major issue facing this segment is the detrimental effect caused by wind gusts on turbine components and local grid stability. Raven's unique control method allows for a variety of operational modes. For example, the Raven system allows control over the level of power extraction in the generator; this control can determine how the turbine responds to a wind gust. The turbine management system could choose to let the energy of the gust go by and there by reduce stress on the blades and tower. Alternately, the management system could briefly store the energy of the gust in the faster turning blades and subsequently draw the power out smoothly over a period of time; reducing voltage pulses on the grid.

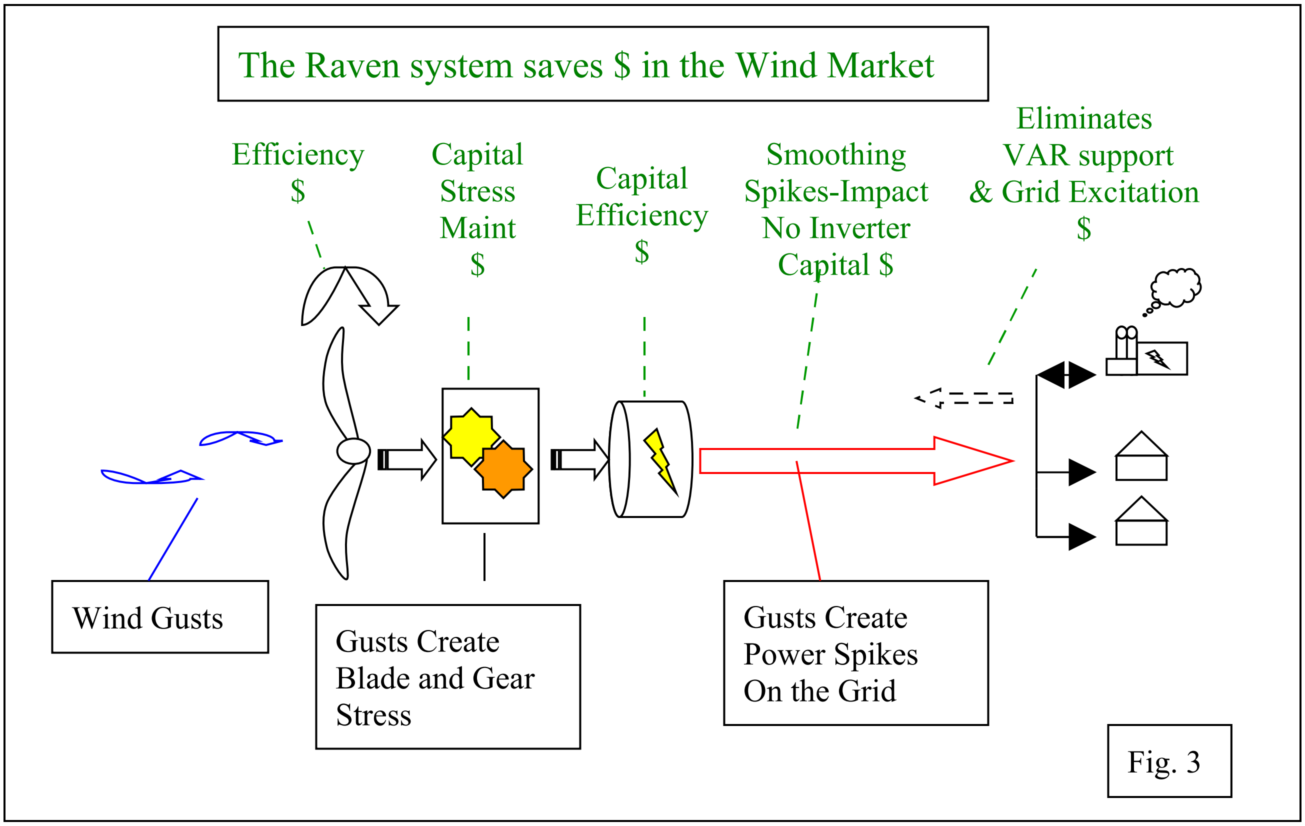


Fig. 3

Capital Cost benefits

Fig. 4 shows the first-cost opportunity offered by the Raven system. In this example the various costs for a 1.5 MW wind turbine system utilizing a doubly fed induction system are compared to those estimated for a Raven system. The relative costs are based on estimates and data from two studies compiled by the National Renewable Energy Laboratory (NREL).

- Wind Turbine Design Cost and Scaling Model, Dec. 2006 Report NREL/TP-500-40566 (see pg. 35 for system cost estimate), and
- Windpact Advanced Wind Turbine Drive Train Design Study Aug. 2003 NREL/SR-500-33196 (see pg. 13 for summary of systems)

Extrapolating cost savings is difficult; we have tried to find a middle ground in order to draw attention to our advantages without over stretching our best engineering estimates. The doubly-fed induction generator is used as the "base-line" system in both studies. The proposed Raven system closely parallels a multi-induction machine design used in the drive train study. NREL's multi-induction design, similar to Clipper Wind Power, used eight 188kW – 1800 RPM generators driven by a single turbine. A similarly sized Raven system avoids various system costs (VAR control and support, etc) and allows variable speed operation. It can be seen that variable speed control offered by the Raven system provides substantial cost savings in the required gears and transmission. It also offers significant savings opportunities in the power electronics. Additionally, the simpler gearing and the simpler soft-switching SCR electronics of the Raven system promise more robust performance, in addition to the lower cost, while still providing the operational flexibility and efficiency of variable speed operation. The overall system cost savings are substantial.

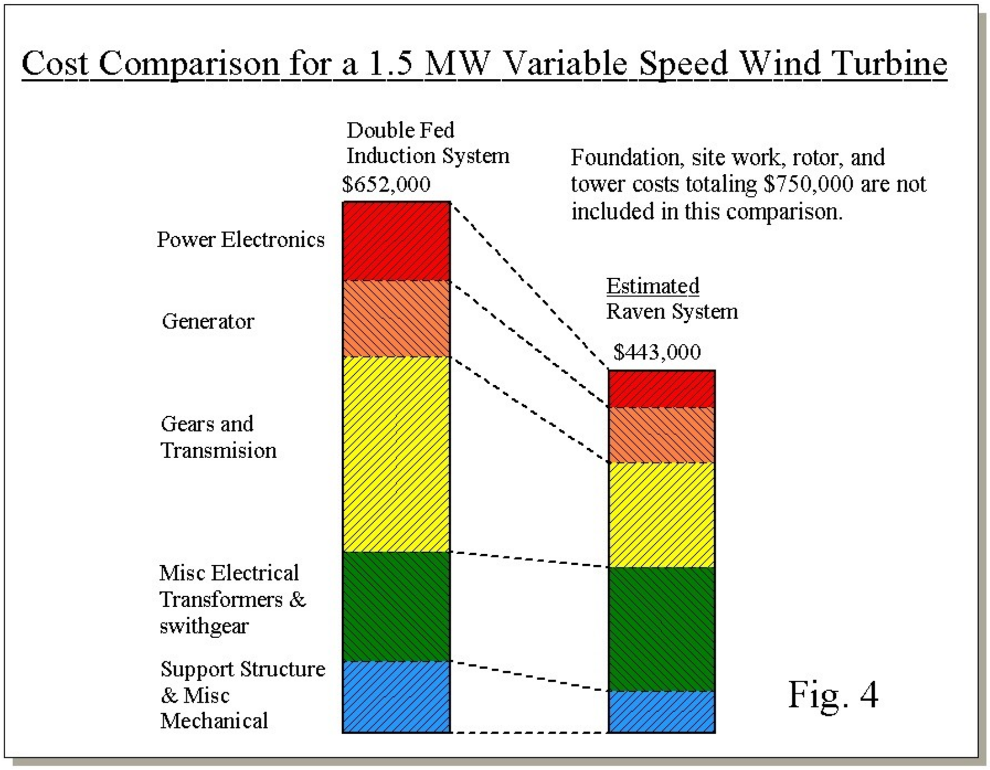


Fig. 4

Moderate speed – Mobile Power and Diesel Powered Generator Sets (600-5000 rpm)

Mobile Power:
The market for on-board AC power is in its infancy. The goal for this market is to generate over-the-road AC power from the operation of the main engine any time the vehicle is running. The current solutions available for on board power range from Raven's belt or PTO driven Blackbird™, PTO driven hydraulic gen-sets, PTO driven synchronous generators, auxiliary diesel or gas powered gen-sets as well as inverter systems. At power levels above 3 kW none of these systems is rated for over-the-road use due to technical issues in the generator drive system in handling the dynamics of the main engine. Additionally, of these systems only inverters and the Blackbird™ are suitable candidates for over-the-road power.

A large near term market for on-board power is the conversion to all electric refrigeration of short and long haul trucks. These units will require as much as 15 kW and are currently powered by auxiliary diesels which significantly impact the fuel consumption, emissions budget and carbon footprint of highway trucks involved in moving frozen and refrigerated goods. "No Idle" legislation is now in place or being considered in a number of states and may force the trucking industry toward using all electric refrigeration unit that can be plugged in to shore power during extended stays at truck stops so that the engine can be turned off.

A solution for this market will involve the development of a specialized over-the-road generator powered by the main engine. Such a generator will be either PTO driven or an in-line design mounted between the engine and the transmission. The cost of the unit will be a significant factor in the success of any design. Due to its simplicity, Raven's technology is well poised to offer a cost effective product that could meet the demanding needs of this market.

Diesel Powered Generator Sets:
As with the other systems described in this paper, diesel generator sets can see improved part loads efficiency with the use of VSG systems. Fuel costs will go down when the engine is allowed to follow its power curve as load varies. Historically, VGS systems have been too expensive for this market but higher fuel costs and the lower cost Raven system could be a critical combination.

High speed turbines – (5000- 30,000)
Steam and other Rankine cycle turbines may operate in the 5-30,000 rpm range: Across this range Raven's variable speed technology can offer gearless drives, simplifying system mechanics along with improving efficiency by allowing the turbine to operate at the best speed for the given power level. This can also be advantageous in controlling combined heat and power cycles, or in extracting power from variable flow energy streams such as solar-thermal or geo-thermal.

Very High speed – Gas Turbine and Micro-turbine Generator Sets

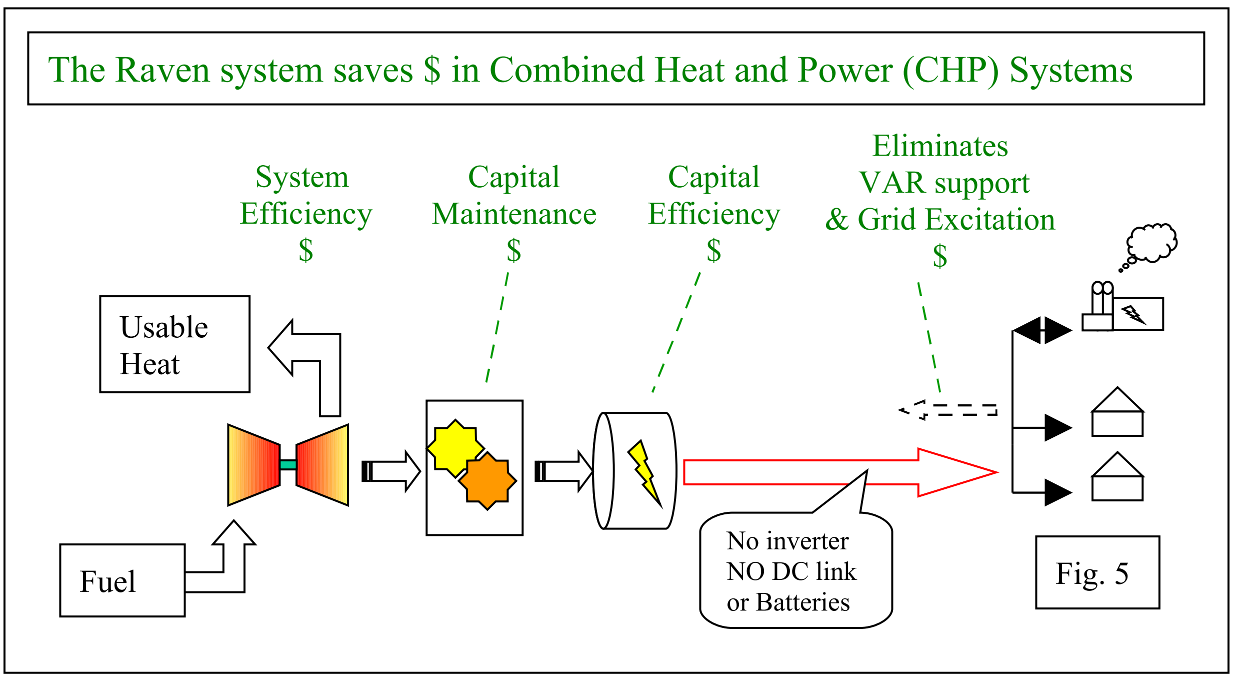


Fig. 5

As described for other systems, Raven's variable speed generator technology can simplify or eliminate gearing and allow for system optimization at part load. Additionally, in co-generation plants the variable speed generator lets the system optimize efficiency while matching to the available thermal energy profile.

Field Modulated Power Generation: a Primer

History

The idea of producing variable-speed fixed-frequency AC power through field modulation of high frequency alternators dates back to at least the middle of the last century. A limited number of demonstration systems were built and, early concepts were patented, by players like Sunstrand Corporation, MIT, and Oklahoma State University.

With support from the US Army and the Ballistic Missile Defense Organization SBIR programs (1995-2001), Raven Technology developed breakthroughs that made **variable-speed** under-hood electrical power practical using the **field modulation** technique. This technology provides 60-Hz 120 VAC power directly from a high-frequency alternator regardless of engine speed, without the costs, losses, and electronic stresses of "hard-switching" and filtering required by inverter technology.

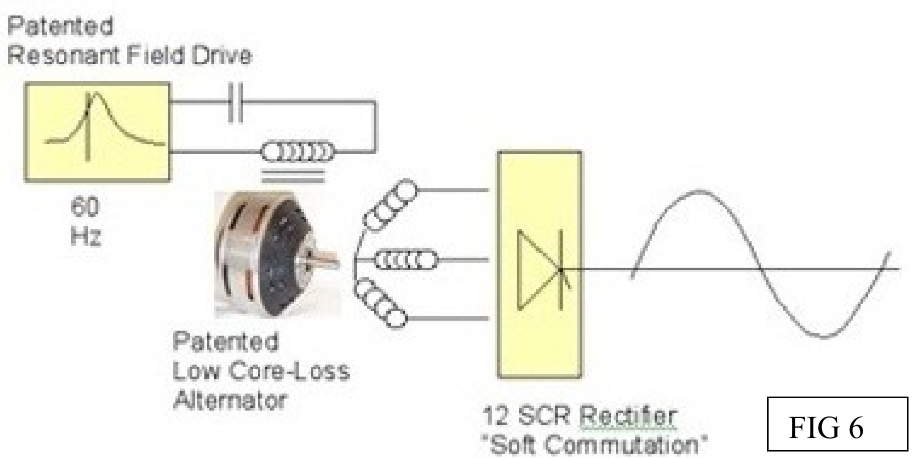


FIG 6

The overall system is shown in FIG 6. The operation is detailed in US Patent 6,051,959.

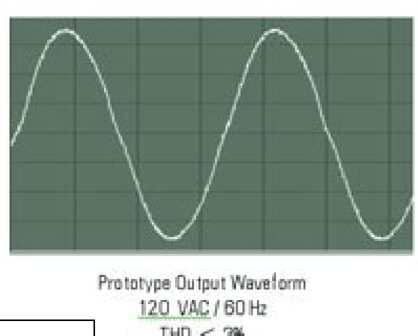


FIG 7

The output of a three-phase high-frequency alternator is rectified into a single output voltage by **natural commutation** of diode-like devices similar to the operation of a typical automobile alternator. The output level of the alternator is controlled by modulating the field coil magnetism with a 60 Hz sine wave. This produces a high quality 60-Hz rectified sine wave output, which is then "unfolded" into a full sine wave, as shown in FIG 7, by **soft-switching** as the current passes through zero.

Key to Raven's success with this simple and robust approach is Raven's patented technique for **"Resonant Excitation"** of the alternator field. Use of resonant circuit techniques efficiently provides the high driving voltages needed to force the magnetic energy into and out of the alternator field 60 times per second. Typical automotive alternator designs are not suitable for this resonant excitation because the quickly changing magnetic field would produce high losses from eddy currents. Raven developed special low core-loss alternator designs which enable this resonant excitation technique. One family of these designs is described in US Patent 6,177,746 B1. In 2009 Raven received US Patent 7,615,904 B2 for new a family of **three-phase** (power frequency) alternators to provide grid type power using the advantages of this field modulation technique.

Raven also holds US Patent 6,570,370 B2 for a technique allowing **automatic tuning** of the modulation system for peak resonant behavior at 60 Hz. This is important because the resonant frequency is subject to dynamic effects from varying output loads.

<u>Patent Protection:</u>

Six patents have been granted on this technology. Raven Technology holds exclusive license rights to this technology and these patents. International patents are pending. (The US Government has a stated interest and royalty-free-right in those patents marked with a (*).)

- (*) US Patent 6,051,959 **"Apparatus for Resonant Excitation of High Frequency Alternator Field"** – Christopher N. Tupper April 18, 2000.
- US Patent 6,133,699 **"Low-Loss Magnet Core for High Frequency Claw-Pole-Type Alternator"** – Christopher N. Tupper, October 17, 2000.
- US Patent 6,177,746 B1 **"Low Inductance Electrical Machine"** – Christopher N. Tupper and Duncan G. Wood, January 23, 2001.
- US Patent 6,175,178 B1 **"Low Inductance Electrical Machine for Flywheel Energy Storage"** Christopher N. Tupper and Duncan G. Wood, Jan 16, 2001.
- (*)US Patent 6,570,370 B2 **"Apparatus for Automatic Tuning and Control of Series Resonant Circuit"** - Christopher N. Tupper and Duncan G. Wood, May 27, 2003.
- US Patent 7,071,657 B2 "**Method and Apparatus for the Production of Power Frequency Alternating current Directly form the Output of a Single-Pole Type Generator"** - Christopher N. Tupper and Duncan G. Wood, July 4, 2006.
- US Patent 7,615,904 B2 "**Brushless High-Frequency Alternator and Excitation Method for Three-Phase Power Generation"** - Christopher N. Tupper and Duncan G. Wood, November 10, 2009.

Additional information about Raven, its products and principals can be found on our website www.raventechpower.com.