Fuel Cell with Novel Power Conditioning

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Abstract

Fuel Cell systems are appearing as commercial products, however the technology is immature and many improvements are expected. Power Conditioning involving conversion from DC to AC is a particular aspect that suffers from poor performance and high cost. A new form of electromechanical Power Conditioner is proposed with the advantages of higher efficiency and lower cost relative to the electronic equivalent.

Keywords: electromechanical converter, fuel cell, chopper

1 INTRODUCTION

The Fuel Cell is now evolving from the developmental stage through to commercial application, however the initial sales volumes are low and the capital costs are high. As development proceeds and sales volumes increase, significant price reductions are predicted. Because of the cost however, stationary Fuel Cells in particular are limited to installations where either there is a cheap source of fuel (e.g. methane from biomass, byproduct hydrogen from process industries), or where a high availability, high quality power supply is required, e.g. UPS (Uninterruptible Power Supply).

The decision to implement a Fuel Cell system is dictated by power quality and availability requirements. Installations are not decided upon lowest capital cost, otherwise a more conventional technology would be chosen. There is little incentive to improve their overall efficiency. This situation however is due for change as major efforts are being made worldwide to introduce hydrogen economies with the intent of reducing carbon emissions and relieving dependence on hydrocarbon fuels. The stationary Fuel Cell is a key component in this development and in the longer term is anticipated to feature in large scale Distributed Generation. The emergence of Distributed Generation is the result the liberalization and de-regulation of the electricity supply industry. The new economic models encourage a smaller percentage of centralized power generation, the balance provided by localized Distributed Generation.

The principle of the hydrogen economy is to electrolyze water using electricity produced from renewable energy sources. Hydrogen will then be distributed via pipelines and other conveyance systems, rather than being distributed by conversion into electricity and transmitted over the power grid system. The large losses associated with transmission over the grid, compared to physical distribution are avoided. Transportation is also anticipated to be a large user of hydrogen and this will increase the overall size of the distribution infrastructure. Hydrogen will therefore be readily available to consumers.

In the interim period, before hydrogen is generally available, hydrogen may be produced by processing hydrocarbon fuels such as natural gas, ethanol, diesel etc. in a reformer.

The types of Fuel Cell suited to stationary applications are phosphoric acid (PAFC), molten carbonate (MCFC), proton exchange membrane (PEMFC), and solid oxide (SOFC). They have the following characteristics:

Table 1.

	Eff. (%)	Operating temp. (°C)	Start-up time
PAFC	40 - 80	150 - 200	1 – 4 hr.
MCFC	60-80	650	2 – 10 hr.
PEMFC	40-50	15 - 80	1 min.
SOFC	60	1000	0.5 – 3 hr.

A grid synchronized Fuel Cell is an ideal Distributed Generator. When operating on hydrogen produced from renewable energy sources, the CO_2 emissions are zero, and even when operating on reformed natural gas, it has significantly lower CO_2 emissions than a diesel engine.

It has also been suggested that the stationary Fuel Cell is suitable for UPS application, however if the available hydrogen store is limited, the facility would normally derive power from the mains, with a fast changeover to the

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Fuel Cell system should the mains fail. Because of their slow start-up times, none of the Fuel Cell systems are able to meet this requirement. The PEMFC system however may be adapted by the addition of a short-term energy storage mechanism such as a flywheel or ultra capacitors, to provide power during its start-up period.

It is predicted that Fuel Cells will eventually enter the Distributed Generation marketplace and so become a consumer of large volumes of natural gas and hydrogen. In order to reduce operational costs, there will be a substantial incentive to improve the system efficiency.

A comparison of fuel conversion efficiency of the Fuel Cell with other technologies is shown in Figure 1 below.

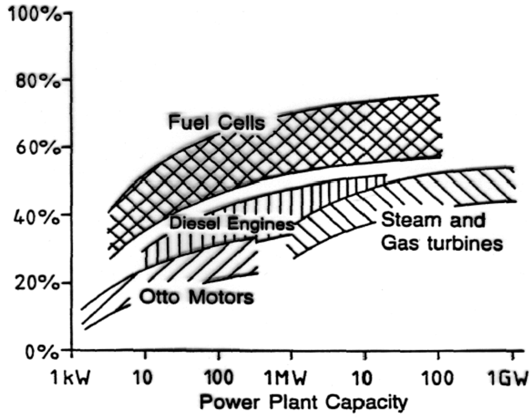

Figure 1. Power plant efficiency vs. capacity

2 POWER ELECTRONIC CONDITIONING

Fuel Cells produce relatively low voltage DC power. In order to be useful, a Power Conditioning circuit converts the DC output of the Fuel Cell into AC to match that of the local Utility supplier. The conditioning circuits are normally electronic and are generally termed PECs (Power Electronic Converters). The Power Conditioning constituent of a Fuel Cell system comprises approximately 20% of the cost, and converts the cell output to useful power with typical efficiency characteristic [1] shown in the graph in Figure 2. A claim of 93% peak efficiency is made for a recently introduced 300kW commercial product [2]. It is therefore a particular area of development that may result in lower capital and improved operating costs.

The graph assumes:

– 250W fixed losses for a 9kW system (2.8% of rated load)
  - No load excitation current losses of transformer in DC-DC converter ~ 90W
  - Switching and conduction losses associated with no load excitation current ~ 10W
  - Controls, gate drivers, and voltage/current sensors ~ 150W

– Other losses vary linearly with load
  - Cooling fans are modulated with load ~50W at rated load
  - Switching and conduction losses in switching devices ~ 280W
  - Conduction losses in passive devices ~50W
  - Results 93% efficiency at rated load (including fixed losses)

– Rated load and Design Peak Load are the same

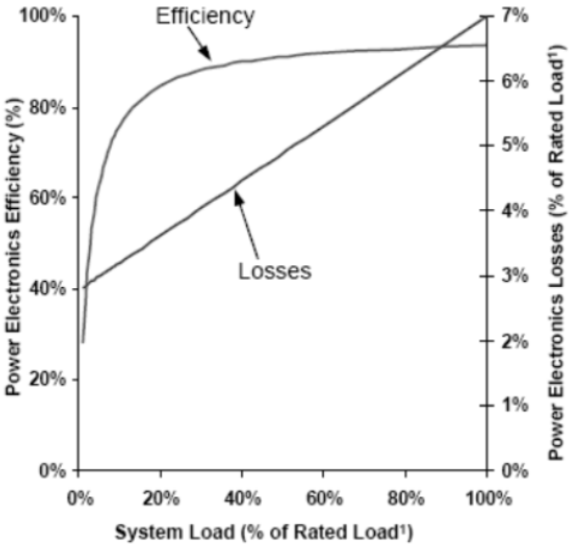

Figure 2. Efficiency of PEC

3 ELECTROMEHANICAL CONDITIONING

A description of a new form of DC to three-phase AC converter: the Homopolar Electro-mechanical Rotary Power Converter (HERPC), has recently been published [3]. The Appendix describes a modified version suitable for Fuel Cell application. By incorporating an IGBT (Insulated Gate Bipolar Transistor) DC chopper [4,5] between the Fuel Cell and the HERPC, an effective Power Conditioner may be constructed. The arrangement is shown in Figure 3.

To prevent damage to the Fuel Cell, the output current must be regulated. Also when fed with hydrocarbon fuels, a reformer will be required which may reduce the output response to 4% min^{-1}. For interim energy storage, ultra capacitors are therefore used [6].

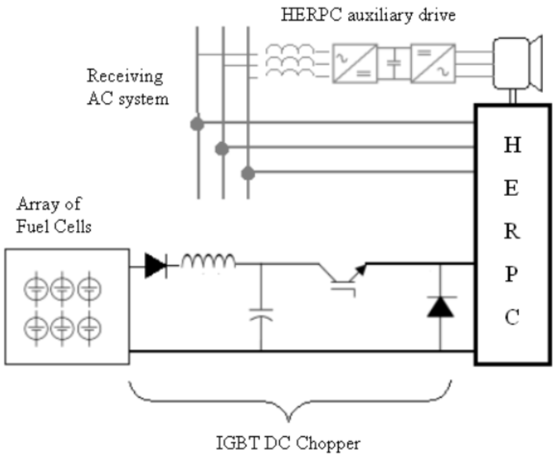

Figure 3. Fuel Cell HERPC Power Conditioning System

The HERPC is akin to both a transformer and a motor. It has primary and secondary windings wound over core limbs with a common core part that rotates. The rotating part however is unlike a squirrel cage induction motor because it does not carry any windings. In a squirrel cage induction motor significant losses occur in the rotor because it is a low voltage device and thus carries high currents with consequent large Joule heating losses.

The HERPC is therefore expected to have efficiency somewhere between that of an induction motor and a transformer. Typically a modern 100kW motor has an efficiency of 95% and a transformer 98.5% or better. A HERPC efficiency of 96.8% is therefore assumed. As for transformer and motor, in general the efficiency in the upper 30% of the load range is approximately constant.

A particular feature of Fuel Cells is the variation of output voltage that occurs between no-load and full load. Typically, a 5kW SOFC delivers a voltage range from 22V to 40V. A 100kW system may be constructed from a series connection of twenty units, which results in a voltage of 440V at full output.

Two paralleled 600V, 150A IGBTs each having a forward voltage drop of 1V, and two 600V, 70A fast recovery diodes each having a forward voltage drop of 1V would be suitable for the chopper duty. A comparison of the overall efficiencies for the PEC and HERPC Power Conditioning systems is shown in Figure 4. The graph assumes 500W (0.5%) for auxiliary equipment power, constant HERPC losses, and negligible DC chopper switching frequency losses.

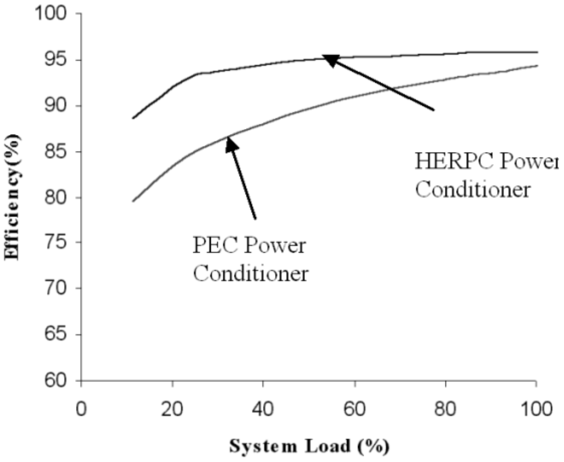

Figure 4. Efficiency of Power Conditioners

Over the load range 30% to 100% the average efficiency of the HERPC Power Conditioning system is 95% whilst that of the PEC Power Conditioning system is 91%.

4 OPTIMAL UTLILIZATION

To optimize Fuel Cell utilization, a technique of switching appropriate numbers of Fuel Cells suited to the load condition, known as ‘level reduction’ has been proposed [7]. The HERPC is also able to complement the ‘level reduction’ technique through use of its input current controller. The HERPC can therefore be controlled using the combination of ‘level control’ and current control to operate at its most efficient current level, and optimize its DC chopper losses and magnetic core losses, for the corresponding load condition.

5 CONCLUSIONS

The preceding sections indicated that over a typical load range, when using a HERPC Power Conditioning system in place of a PEC system, an efficiency advantage of 4% is expected. When discounted over an equipment lifetime of fifteen years, the cost benefit can accrue to sums many times greater than the capital cost of the original equipment.

Particularly because of global warming issues and limited hydrocarbon fuel resources, economic incentives are being introduced to improve power conversion efficiency. In respect of the Fuel Cell, higher efficiency will lead to a lower lifetime cost, compensating the higher relative capital cost in comparison to other technologies. Together with its acknowledged superior reliability over conventional technology, such as diesel generators, the Fuel Cell may become the preferred Distributed Generation system.

A significant capital cost advantage is also anticipated over the incumbent PEC technology. The HERPC based Power Conditioner is mostly based upon rotating electro-mechanical machine technology with costs of about $55/kW, including just a small power electronic component, whereas PEC costs are typically $300/kW [8], (the sum of boost converter plus an active rectifier).

By virtue of the HERPC current control mechanism, and the ‘level reduction’ technique, it is possible to optimize the overall Fuel Cell system performance.

APPENDIX

The following figures illustrate an example of the construction and the principle of operation the HERPC.

Figure A1 shows the basic arrangement for the Rotary Power Converter. The upper part represents a cross section along axis of rotation. Three other cross sections, perpendicular to the axis of rotation, at defining locations, are also depicted.

Figure A2 shows the electrical interconnections between the coils, the source of DC excitation and load burdens connected to the three phase AC output coils.

Figure A3 shows the mathematical function used for a particular shape of the stator AC winding limb face.

Figure A4 shows the progression of the magnetically conductive portion of the rotor (rectangular section) across the stator limb faces at intervals of 30° degrees.

Figure A5 shows the phase relationship of the flux, the DC portion flowing in the stator body and the AC portion flowing in the AC stator limbs.

Each AC phase winding has coils that encircle each stator limb that bears a pole, in the respective phase set. A principal winding, has coils that encircle all the stator limbs that bear poles, on all the phase sets. The principal winding is wound such that with a constant DC source, the flux always flows either radially inwards or radially outwards in all pole bearing stator limbs.

Energy conversion is performed by varying the reluctance of the three-phase sections of the magnetic circuit through turning the rotor.

The rotor has no windings. Its function is to divert the magnetic flux on a time varying basis through each of the three-phase windings, on the stator pole limbs. It consists of some magnetically conducting portion, and some non-magnetically conducting portions. The non-magnetic portion, are required to channel the flux and prevent magnetic short circuits.

The output AC waveforms are determined by the shape of the AC winding limb faces. The induced AC voltage is proportional to the rate of change of flux passing through the winding. The flux however is distributed in proportion to the reluctance of the magnetic circuits - which is in turn proportional to the overlapping areas between the passing rotor and stator faces.

The mathematical function used for a particular shape of the stator AC winding limb face is shown in Figure A3. It shows an area that changes in the form of a sinusoid. It is created from a function that is itself the combination of a positive and negative sinusoid.

At any one time, the sum of all the three-phase AC fluxes is equal to the flux flowing through the stator body. The sum of all the three-phase AC fluxes also equates to the total flux generated by the principal winding. The reluctance of the stator body, and all magnetic circuit paths in parallel with it remain constant.

An auxiliary motor drives the rotor, at the appropriate speed to generate the desired output AC frequency. Unlike an alternator, no electromagnetic restraining force acts. The driving torque is required for inertial accelerations and to counter friction and windage losses.

The magnetic circuits are arranged such that flux links through windings rather than cutting across conductors. The Lorentz force law (F=B.I.L) that applies to generators is therefore minimal. Restraining forces on the rotor are those due to friction and windage.

A non-magnetically conductive spacer is incorporated in the stator body to facilitate input current control. The spacer is secured by means of a non-magnetically conductive locating pin. By adjusting the spacer, the input current to output voltage ratio may be altered.

The cross sections in Figure A1 show two AC winding coils per phase. As the rotor turns through one complete rotation, one frequency cycle of flux passes through each of the coils. Figure A2 therefore shows two series connected coils per phase, resulting in two cycles of output current per revolution of the rotor.

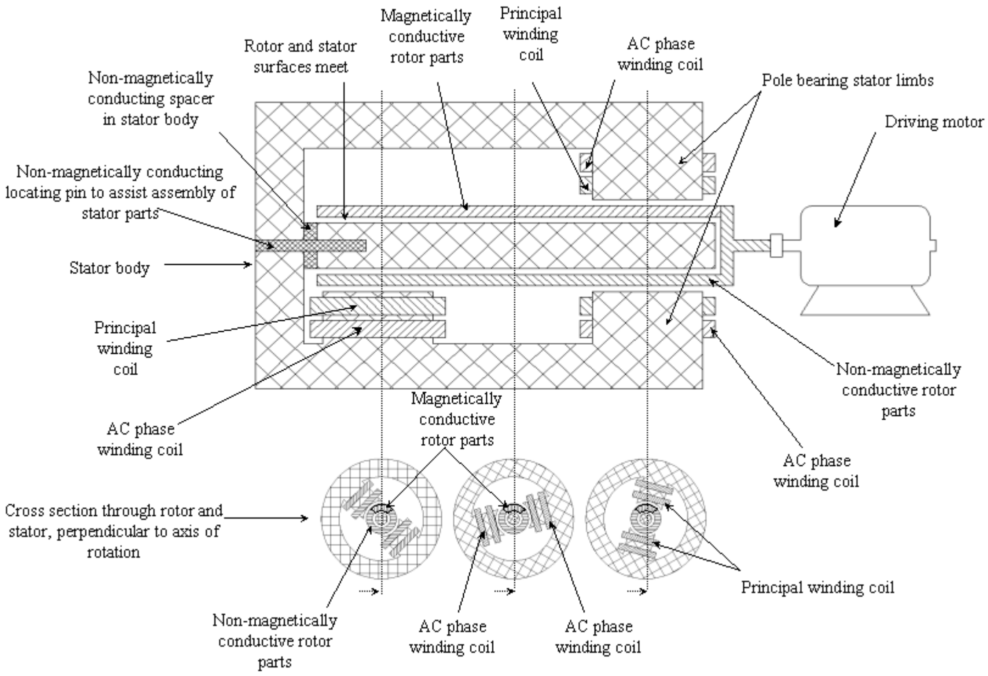

Figure A1. Basic arrangement for HERPC

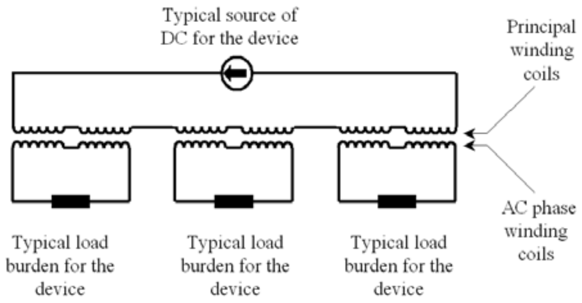

Figure A2. Electrical interconnections between the coils

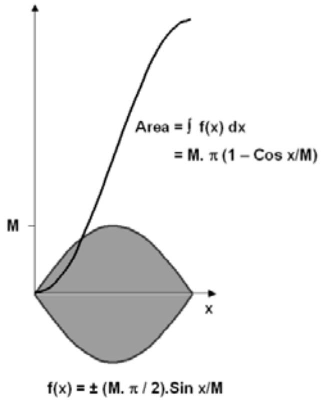

Figure A3. Function of stator AC winding limb face

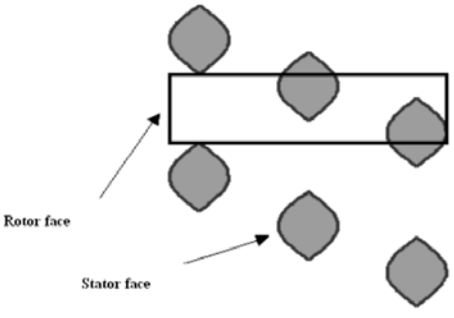

Figure A4. Progression of rotor across stator limb faces

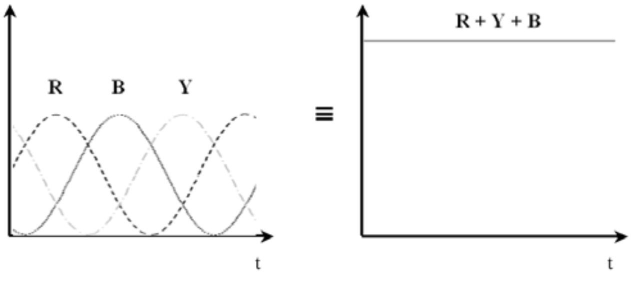

Figure A5. Phasors during inverter operation

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BIOGRAPHY

Michael Owen graduated in Electrical & Electronic Engineering from the University of Manchester in England in 1974. In 1978 and 1980 respectively he was awarded an M.Sc. and Ph.D. in Power Systems by UMIST.

He completed a graduate apprenticeship with the switchgear company Reyrolle, and subsequently worked as a power systems analyst for the Central Electricity Generating Board (CEGB now NGT).

He further developed his career at GEC Transmission & Distribution (now Areva) where he led a team that developed the 'Master Controls' for the England to France 2000 MW HVDC cross channel link.

He has recently been employed by Kellogg Brown and Root on offshore Wind Farm development projects.

He has previously published research papers on power systems protection, computer modelling of power transformers and power conversion, and holds power systems protection patents. In 2004 he chaired the Electric Machines, Power Electronics and Power Plants Control session at the IEEE's Mediterranean Electrotechnical Conference.

Dr. Owen is a member of the Institution of Electrical Engineers.