ANALYSIS AND DESIGN OF POWER CONVERTER FOR FUEL CELL POWER CONDITIONING SYSTEM

Soo-Bin Han, Bong-Man Jung, Sun-Gun Lee, Dong-Ryul Sin, Soo-Hyun Choi

Electric Energy Division
Korea Institute of Energy Research
71-2, Jang-Dong, Yusong-Gu, Taejon 305-343, Korea
Phone: +82-42-860-3121
Fax: +82-42-860-3102
E-mail: sbhan@kier.re.kr

ABSTRACT – **Power conditioning system, especially for power converter, is considered for the fuel cell power plants. Various characteristics of the fuel cell are analyzed and various choices of power converters are considered. One of the main converters, the boost type is selected and analyzed as an example.**

I. INTRODUCTION

Fuel cells have emerged in the last decade as one of the most promising new technologies for meeting the energy needs well into the 21st century. Unlike other conventional power plants, fuel cell plants that generate electricity and usable heat can be built in a wide range of sizes from few kW suitable for mobile power supply, to above 100 megawatt plants that can add baseload capacity to utility power plants [1-2].

Fuel cells are similar to batteries in that both produce a DC current by using an electrochemical process. Two electrodes, an anode and a cathode, are separated by an electrolyte. Like batteries, fuel cells are combined into groups, called stacks, to obtain a usable voltage and power output. Unlike batteries, however, fuel cells do not release energy stored in the cell or run down when the energy is gone. Instead, they convert the energy in a hydrogen-rich fuel directly into electricity and operate as long as they are supplied with fuel. Fuel cells emit almost none of the sulfur and nitrogen confounds released by conventional generating methods, and can utilize a wide variety of fuels: natural gas, coal-derived gas, landfill gas, biogas, or alcohol.

The fuel cell has many favorable characteristics for energy conversion as following:

- Environmental acceptability: Because fuel cells are so efficient, CO_2 emissions are reduced for a given power output. By 2000, fuel cell power plants are projected or decrease CO_2 emissions by 0.6 MMT of carbon equivalent.

  Efficiency: Dependent on type and design, the fuel cells plant electric energy efficiency ranges from 30 to 60 percent (LHV). The fuel cell operates at near constant efficiency, independent of size and load. The fuel cell is very responsive, cold starting within hours and idle to full load in minutes.

  Modularity- Fuel cell is inherently modular. The fuel cell power plant can be configured in a wide range of electrical output, ranging from a nominal 25kW to greater than 50MW for the natural gas fuel cell to greater than 100MW for the coal gas fuel cell.

And other advantages such as distributed capacity, fuel flexibility and co-generation capability must be also notified.

PEM (Proton Exchange Membrane) fuel cell appears as one of the most promising energy conversion technologies presently under development. They are suitable for decentralized combined heat and power production as well as for mobile applications. Especially, PEM fuel cells are considered to be a strong candidate to become a primary power source for vehicular applications because of their characteristics such as high power density, high efficiency, fast response to load changes, and short start-up time. Almost major car manufactures have already demonstrated prototype fuel cell vehicles (Daimler-Benz, Toyota, Renault), or announce their plans to build one (Ford, Chrysler, General Motors, Peugeot, Honda, Volkswagen /Volvo) [2-3].

In this paper, how to develop the fuel cell power conditioning system, especially for PEM type, is discussed. Inherent I-V characteristics of fuel cell are summarized and various choices of power converters are considered. One of the main converters, the boost type is selected and analyzed as an example.

Proceedings ICPE '98, Seoul

II. CHARACTERISTICS OF FUEL CELL

It is known that fuel cell performance will degrade if the fuel cell is left in its high voltage level (such as above 0.8 V/cell), and it will also degrade due to the reversed polarity effect that may occur if the fuel cell is at too low voltage level. When the fuel cell is left in a high voltage state, an electrochemical reaction may be caused by any residual gases that remain in the fuel cell if the power generator system is stopped. This reaction also produces a high voltage when the system is placed under no load condition.

Fig. 1 shows a relation between gas and electrical state in a fuel cell. When the system starts, a fuel cell rising temperature period is necessary before fuel gas and oxygen gas are to be fed into the fuel cell. Once any gas is fed into the cell, the cell voltage is increasing rapidly before current occurs. In this period, open circuit voltage condition must be checked. In normal condition, current increases but voltage decreases with increasing gas. When the system stops abruptly, peak voltage also occurs in the fuel cell.

Fig. 2 shows that an I-V characteristic curve where the fuel cell voltage decreases with increasing current from 100% in the no load condition to about 40 ~ 50% in the full load condition. Normally, the peak power occurs near the rating current. A discharging load is needed in the fuel cell system to avoid the high voltage state produced by the electrochemical reaction. Some fuel cell system uses resistance load directly between two fuel cell electrodes as discharging load. For hybrid vehicle applications, battery charging from fuel cell is operated as a kind of discharging load. So the operating load range is located between a discharging load and a maximum load which is normally above a full load.

Fig. 3 shows efficiencies of both only the fuel cell stack and the fuel cell system including the fuel supplying system. Both stack efficiency and system efficiency decrease with the load but the system efficiency is high near the 20% of the peak power and flatter compared to that of the stack. System efficiency is above 45% over all range that is much higher than that of conventional power plants. Practical operating curves are changed by various fuel/air supplying conditions such as fuel/air flow rate, pressure, and temperature.

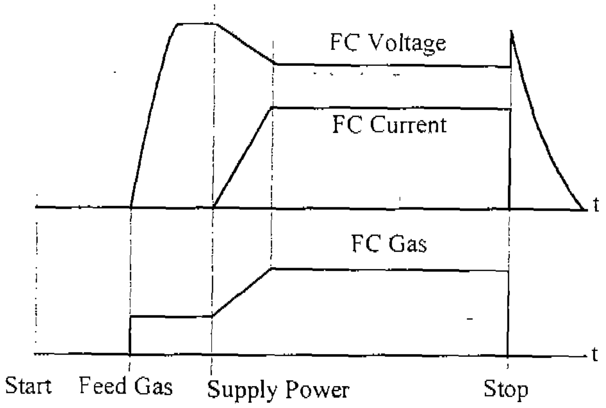


Fig. 1. Operational mechanism in the fuel cell.

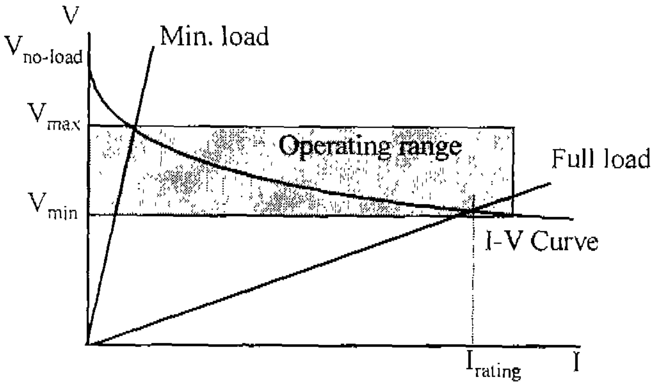


Fig. 2. I-V characteristic curve of the fuel cell.

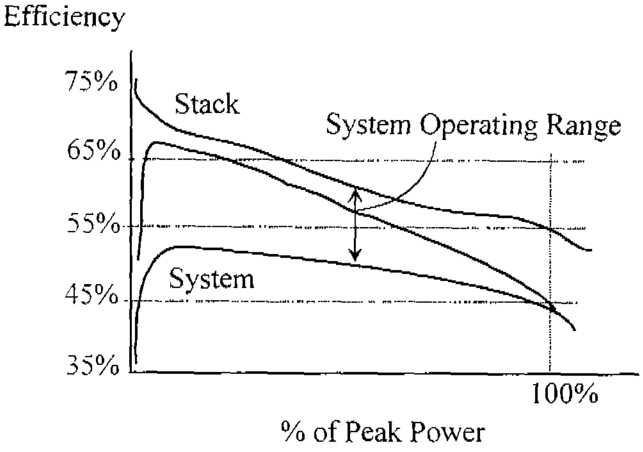


Fig. 3. Efficiency - Power characteristic curve

III. FUEL CELL PLANT CONTROL

A basic control philosophy of a fuel cell plant system is to manage effectively the combined fuel cell system in which fuel cell stack and power converter including inverter have fast response times, but reforming system has very slow response time as shown in Table 1.

Practically, control system should be capable of

Table 1. Time constants of fuel cell system.

	Reformer	Fuel Cell	Converter/ Inverter
Time Constant	Several ten seconds	Several msec order	msec order
Operation Principle	Chemical reaction	Electro-chemical reaction	Electrical reaction

detecting any load change and varying the flow rate of the fuel cell and the reformer in accordance with demand. The method of output control is different for independent power sources and grid-connected systems.

For independent power sources as Fig. 4-a, generally applied to small scale on site plants, (1) the converer/inverter is controlled by detecting the change in output voltage due to load change, and (2) the gas flow to the fuel cell is controlled by the corresponding value of the output dc current, which is equal to the input of the converter/ inverter. For example, when the output current of a fuel cell increase, the inlet valve of the reformer is correspondingly opened to increase the supply of natural gas to the reformer. If the fuel cell output current increases rapidly, only the hydrogen stored in the piping between reformer and fuel cell must be fed instantaneously to the fuel cell, because the reformed hydrogen should be equipped in front of the fuel cell.

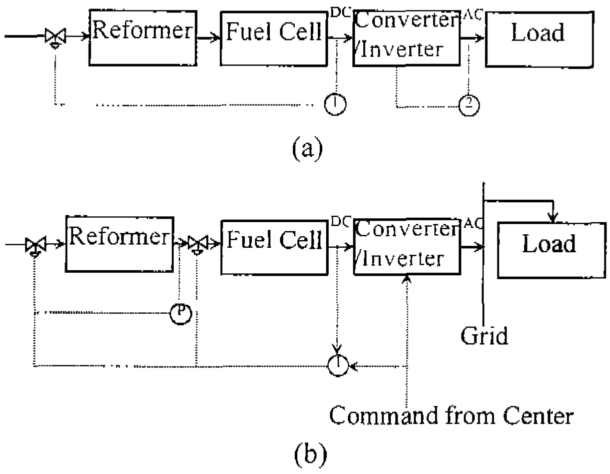
In case of electric utility applications as Fig. 4-b, a large-capacity plant is connected to the grid and inverter output is usually controlled by the load demand from the central control center. In most cases the control of gas inflow to the reformer and fuel cells is performed simultaneously. An additional valve is necessary to control the flow balance between the inlet and outlet of the reformer. The control system controls opening of the valve by detecting the outlet pressure of the reformer.

IV. SELECTION OF CONVERTER TOPOLOGY

The output voltage of the fuel cell stack decreases sharply as the current increases. In the worst case, the output voltage at rated current is almost half of that at no load. It is uneconomical to design an inverter to meet a very wide range of input voltage and constant output. This would result in a large equivalent capacity and poor performance. To avoid this, a chopper is connected to converter the broad range of voltages to constant voltage, which is to be fed to the inverter. The role of the chopper is to convert the input dc voltage to another dc voltage, and is classified into two types: a step up chopper and a step down chopper. However, the total system cost including converter (chopper) and inverter might be higher, and the system efficiency might be lower compared to that of single inverter unit; hence, the system design should be determined from the comparison of merits and demerits of these systems. Until now, it is a major tendency to use power conditioning system include both converter and inverter for AC commercial output, and use only converter for DC applications.

There are various topologies of converters each exhibiting different characteristics. Simple inductor coupled converters may provide a means of lifting (Boost converter) or reducing (Buck converter) the voltage from the fuel cell to interface to a common DC link. The output of these converters is not isolated from the input, however in the case of a power conditioner for a fuel cell, this may not be necessary.

A further consideration in the design of a converter is the characteristics of the input current to the converter, as this has to be sourced by the supply (fuel cell). The inherent switching action of converters gives rise to a pulsating input current in most cases including bridge type converter, this may be undesirable for some supplies. But a boost topology converter topology exhibits a continuous input current, albeit with a superimposed ripple, which may be more suitable for constant power delivery from a supply. Another topology such as resonant converter also need a fast pulsating current from the source, which is undesirable to the fuel cell stack.



(a)

(b)

Fig. 4. Principle of fuel cell plant control:
(a) independent power plant, (b) grid-connected power plant.

It is notified that the fuel cell can only supply the ower to load but cannot storage the power from the oad (or other electrical sources). So fuel cell must be rotected from the reverse current flow by connecting he serial diode. In this case, the boost type topology is uitable to use because it has a serial diode in the opology itself while the bridge type topology need dditional diode.

Fuel cell is a low voltage-high current source because ingle cell of 0.6V can supply above 300A, which is, of ourse, dependent of the area of the cell. For examples, vhile 5-10kW PEM stack is composed of 100 cells vith a size of 30cm*30cm*70cm and a current output f 70-150 amp, 30-60kW stack of 100 cells has a size f 45cm*60cm*70cm and a current output of 450-900A 3]. Although stacked fuel cells are used for pplications, most fuel cell stack cannot avoid such a haracteristic due to the limited stacking technology.

V. ANALYSIS AND DESIGN OF BOOST TYPE CONVERTER

For a successful design of a boost type converter shown in Fig. 5 for fuel cell applications, following important points must be considered.

i) Start operation [4]:

When the input voltage source V_d is first applied and the active shunt switch is off, the input inrush current is limited only by the characteristics of a low pass filter network formed by r_L, L, and C. The shape of the inrush source current transients is one-half cycle of a damped sinusoid as shown in Fig 6.

The maximum value of this transient may be many times that of the steady state average value of the fuel cell source current. The high peak current can produce damage to filter elements or to the fuel cell. For these reasons, converter should have an ability to limit the amplitude of inrush current.

One of solutions is to use a soft starting sequence in which the duty ratio of switch is controlled as a small value until the output capacitor is charged to a reasonable voltage level. In Fig. 7, the duty ratio is 0.1 during first 5msec, then becomes 0.625. This shows that the inrush current decreases to an allowable level and the overshoot of output voltage also decreases. The shape and magnitude of the inrush current are much dependent on the characteristic impedance, Z_o, as well as duty ratio. The magnitude becomes small for the low duty ratio and the large characteristic impedance.

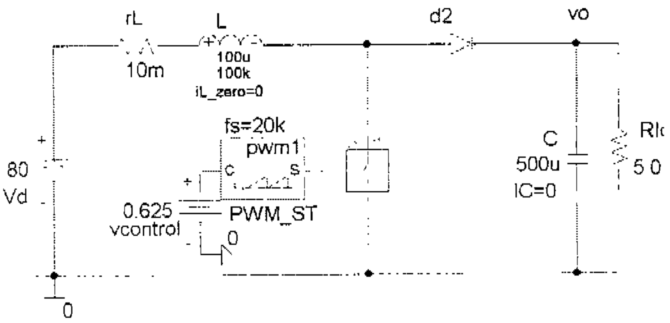


Fig. 5. Boost converter.

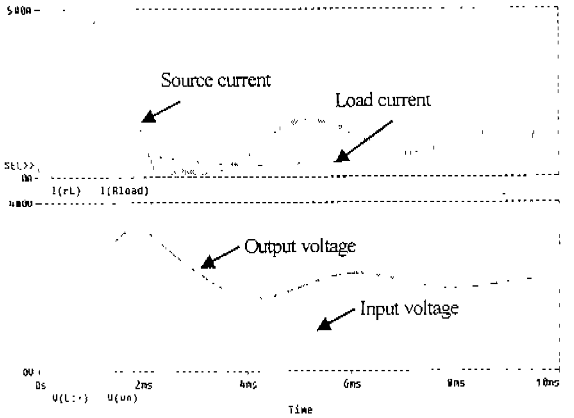


Fig. 6. Inrush current at start up.

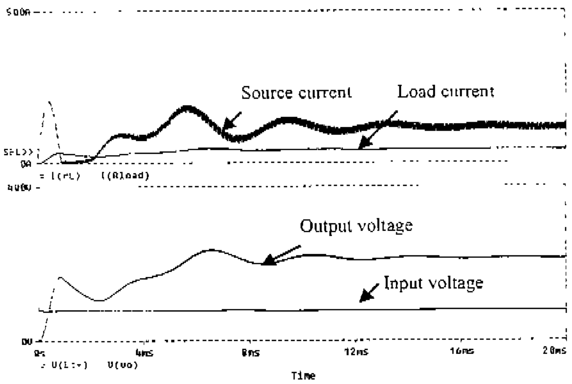


Fig. 7. Inrush current in a case of soft start.

ii) Protection from no load condition:

A situation that the output loading of a boost converter is removed is frequently encountered in real applications. In this case, overvoltage or stress problems due to unloading can be eliminated by adding auxiliary circuitry in the boost control system after sensing an overvoltage condition and then reducing switch duty ratio D to zero or a low value.

iii) Non-minimum phase characteristics:

The problem of stabilizing the control loop over wide range operating conditions is not easy to solve because the control to output transfer function has a positive zero. This right half-plane zero appears as a consequence of the switching action. and seriously complicates the design of control loop. For system with the same magnitude characteristic. the range in phase angle of the minimum phase transfer function is minimum for all minimum phase system and the transfer function can be uniquely determined from the magnitude curve alone, while the range in phase angle of any non-minimum phase transfer function is greater than this minimum. Non-minimum phase system is slow in response because of its faulty behavior at the start of response that the initial slope of the output response is negative for a positive input change as shown in Fig 8.

One solution for the control is to use a current mode control instead of controlling the output voltage [5] and another one is to use leading edge modulation for PWM [6]. Other various control methods including nonlinear control and smith predictor control are also used for output voltage control.

iv) Possible voltage gain:

Practical gain of the boost converter is limited by the parasitic losses in the components such as inductor, capacitor, switch and diode. The current of the fuel cell is very high so the converter should have low parasitic resistance for a high gain. Normally, when the duty ratio is above around 0.8, the losses are abruptly increased even to decrease the gain. In fuel cell systems flowing above several hundred amperes, possible maximum gain would be about 3~5. Fig. 9 shows that the voltage gain is influenced by an equivalent parasitic resistance, r_L, of Fig. 5 with the same circuit and control conditions.

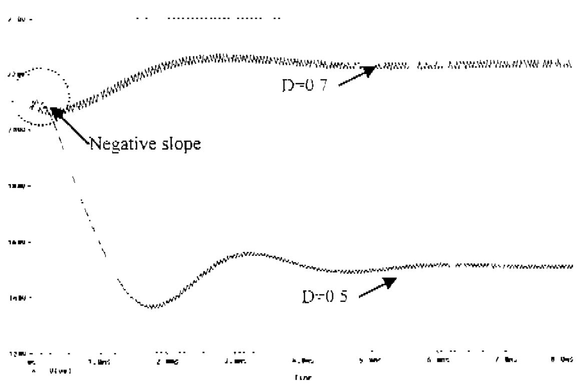


Fig. 8. Start response on non-minimum system.

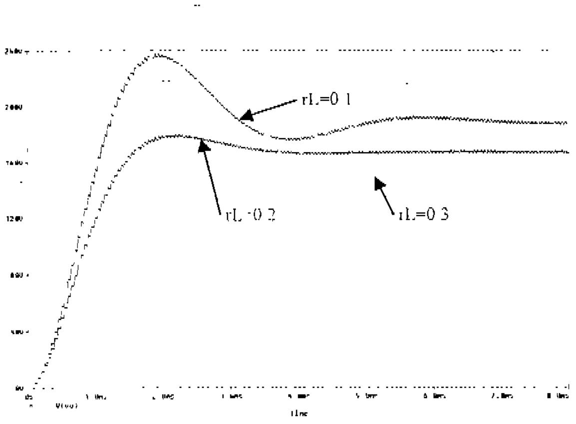


Fig. 9. Gain reduction by parasitic component

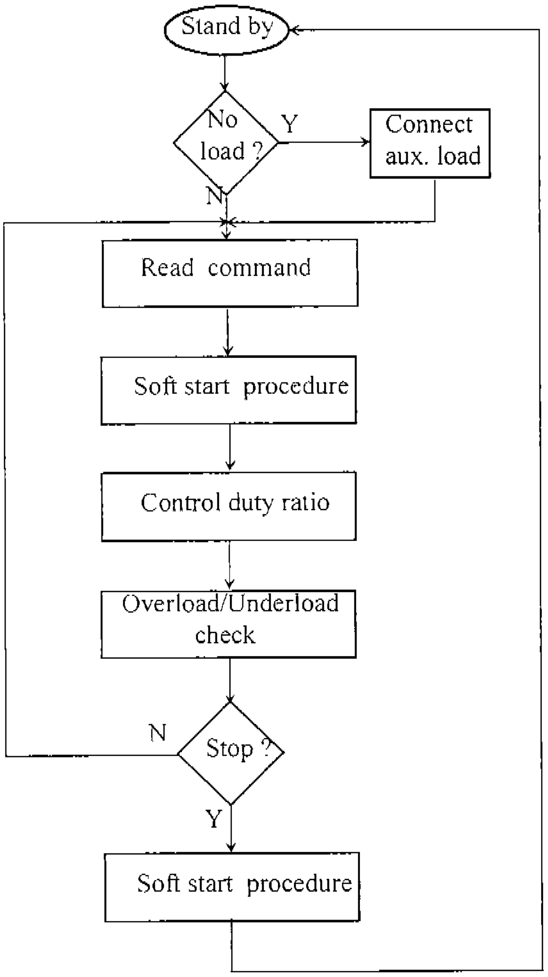


Fig. 10. Flow diagram to control fuel cell converter.

Fig. 10 shows that a necessary sequence to control the boost converter for fuel cell systems. The controller should check whether the load is in an open state. If no load state, auxiliary load is connected. After reading the command, soft starting sequence, in which the duty ratio increases from a minimum value to a set value, starts to operation. Then, proper duty ratio is calculated by a given control algorithm. After normal control action, overload and under-load are monitored for a safety. Thereafter, such a control sequence is repeated until stop sign.

VI. CONCLUSION

The power converter for fuel cells, which have properties such as low voltage-high current source and wide range variations of I-V curve according to the load, has unique characteristics described above sections. Although many choices are possible for using the power converter, traditional topology called boost converter has many advantages for fuel cell applications. But it has also limitations in voltage gain and control. So it is necessary to solve this problem economically and derive more suitable topology for fuel cell applications until now.

REFERENCES

[1] G.A. Phillips. J.H. Vogt,. J.H.Walton, "Inverters for Commercial Fuel Cell Power Generation," IEEE Trans. on Power App. And Sys., pp.994-953, 1976.

[2] R.Mosdale, "Commercializing Fuel Cell Vehicles 97," Intertech Conference Records of Commer-cializing Fuel Cell Vehicles 97, 1997.

[3] A.Maggiore, "Solid Polymer Fuel Cells of Industrial Interest," Intertech Conference Records of Commer-cializing Fuel Cell Vehicles 97, 1997.

[4] R. P. Severns, G. Bloom, "Modern DC to DC Switchmode Power Converter Circuit", VNR, 1985.

[5] R. Redl and N. Sokal, "Current Mode Control, Five Different Types, Used with the Three Basic Classes of Power Converters," Power Electronics Specialists Conference Record, pp. 771-785, 1985.

[6] D. M. Sable and B. H. Cho, "use of Leading Edge Modulation to Transform Boost and Flyback Converters into Minimum-Phase-Zero Systems," IEEE Trans. Power Elect. , vol. PE-6, no. 4, pp.704-711, 1991.