Optimum Fuel Cell Utilization with Multilevel DC-DC Converters

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Abstract—Static characteristics of fuel cells show more than a 30\% difference in the output voltage between no-load to full-load conditions. This inevitable decrease, which is caused by internal losses, reduces the utilization factor of the fuel cells at low loads. Additionally, the converters fed by these fuel cells have to be derated to accommodate higher input voltages at low currents. To increase the utilization of fuel cells and to avoid derating of semiconductors, this paper proposes a level reduction control using a multilevel DC-DC converter. Level reduction is done by inhibiting a certain number of fuel cells when the load current decreases. The inhibited fuel cells can be used in other applications such as charging batteries to further increase their utilization and the efficiency of the system.

Keywords—Fuel cells, DC-DC power conversion, multilevel systems, power distribution, interconnected power systems

I. INTRODUCTION

Human dependence on electricity is growing faster with time. Coal, oil, and other energy sources have been used to generate electricity for more than a century. Today, conventional fossil energy supplies, such as oil, coal and natural gas, are rapidly depleting, and NO\textsubscript{x}, CO\textsubscript{2} and SO\textsubscript{2} air pollution due to fossil fuels is a major environmental concern. To overcome these problems, renewable energy sources must replace fossil energy sources [1,2].

Fuel cell technology is one of the options for renewable energy sources. The electrical efficiency of a fuel cell can be greater than 70\% in theory (the current technology is only capable of reaching around 45\%). The cogeneration of electrical energy and heat improves the exploitation of the primary energy source. The product of the chemical reaction in fuel cells is H\textsubscript{2}O when H\textsubscript{2} is used as fuel, and no pollutants like SO\textsubscript{x} or NO\textsubscript{x} are produced; therefore, the fuel cells are environmentally cleaner than traditional generators.

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U.S. Department of Energy’s Solid-State Energy Conversion Alliance (SECA) program [3] is targeting solid oxide fuel cell (SOFC) modules in the 3–10 kW range to be made available for residential applications [4-6]. In addition to residential use, these modules are expected to be used in high power applications such as apartment buildings, hospitals, schools, etc. For example, a hospital might require a 250 kW power supply. To provide this power using the SOFC modules, 25 of the 10 kW modules would be required. These modules can be integrated in different configurations to yield the necessary power. The multilevel converter family is one of the options for this integration because they require multiple dc inputs.

Multilevel converters are of interest especially in the distributed energy resources area because several batteries, fuel cells, solar cells, wind turbines, and microturbines can be connected through a multilevel converter to feed a load or the ac grid without voltage balancing problems. Another major advantage of multilevel converters is that their switching frequency can be lower than a traditional converter, which means reduced switching losses and increased efficiency.

In this paper, a multilevel DC-DC converter is used to overcome some problems associated with the fuel cell V-I characteristics. The static (V-I) characteristics of fuel cells show more than a 30\% difference in the output voltage between no-load to full-load conditions (Fig. 1). This inevitable decrease, which is caused by internal losses, reduces the utilization factor of the fuel cells at low loads. Additionally, the converters fed by these fuel cells have to be derated to accommodate higher input voltages at low currents. To increase the utilization of fuel cells and to avoid derating of semiconductors, this paper proposes a level reduction control technique for a multilevel DC-DC converter.

II. FUEL CELL V-I POLARIZATION CURVE

The general V-I polarization curve for a single-cell fuel cell is shown in Fig. 1 where the reduction of the fuel cell voltage with load current density can be observed. This voltage reduction is caused by three major losses [7-9]. At low current densities, the dominant loss is the activation loss, which is caused by the slowness of the reactions taking place at the electrode surface. The voltage drop created by the activation loss is highly non-linear.
Ohmic losses are caused by the flow of electrons through the electrolyte and through the electrodes. The electrolyte should only transport ions through the cell; however, a small amount of fuel diffusion and electron flow occurs. Ohmic losses are essentially linear, i.e. proportional to the current density. Decreasing the electrode separation and enhancing the ionic conductivity can reduce the ohmic losses.

The final loss component is the gas transport loss at higher current densities. As the reactant is consumed at the electrode, the concentration of the surrounding material reduces because not enough reactants and products are being transported to and from the electrodes. The output voltage decreases with the decrease in the concentration.

Fig. 2 shows the static characteristics of a 10kW SOFC module. In [10], static characteristics of single cell SOFCs are given. To get the necessary voltage and power output ratings, it was assumed that these single fuel cells can be stacked in series and parallel. The resulting V-I curve in the figure shows a no-load voltage of $V_{F, NL} = 74.2\text{V}$ and a full-load voltage, $V_{F, FL} = 42.91\text{V}$. The remainder of the paper will use these characteristics for calculations.

III. FUEL CELL POWER ELECTRONICS INTERFACE

Today, there is not yet a standard rating for the output voltage of a fuel cell. Present fuel cells are typically producing dc voltages between 20V and 50V at full-load. When one of these fuel cells is connected to an inverter, they will not be able to produce ac grid level voltages. As shown in Fig. 3, a DC-DC boost converter is required to boost the voltage level for the inverter. This boost converter, in addition to boosting the fuel cell voltage, also regulates the inverter input voltage and isolates the low and high voltage circuits. The inverter for a residential application is either single- or dual-phase.

This paper focuses on high power applications where several low power (3-10kW) fuel cell modules are available and they have to be connected together. There are several options to integrate them using power electronics: series, dc-link, high-frequency ac-link, or multilevel configurations. More information on these configurations can be found in [11]. The easiest and the most preferred approach would be the series configuration; therefore, that configuration will be taken as a base case in which to compare other more novel cases against it.

A. Case A

In this approach, fuel cell modules are connected in series and fed to an inverter as shown in Fig. 4. This approach is similar to the single module power electronics interface shown in Fig. 3. The only difference is that since the fuel cell output voltage in this case is enough for the inverter to produce ac grid level voltages, there is no need for a voltage boost.

The problem with this approach is that the fuel cell voltage varies with load current; it is low at full-load and much higher at no-load.

Assume that the inverter needs a dc-link voltage, $V_{dc}$, then the number of fuel cells required to obtain $V_{dc}$ at full-load can...
be found by

\[
    n_{\text{total}} > \frac{V_{dc}}{V_{fc,FL}} \tag{1}
\]

where \( n_{\text{total}} \) is the number of fuel cells required and is an integer, and \( V_{fc,FL} \) is the voltage of a fuel cell module at full-load.

A three phase inverter running at the border of the linear PWM region with a modulation index of 0.785 requires 396.3V dc-link voltage to produce 220Vrms. Considering that \( V_{fc,FL} = 42.91 \)V (Fig 2), the number of fuel cell modules required to produce this dc voltage is

\[
    n_{\text{total}} > \frac{V_{dc}}{V_{fc,FL}} = \frac{396.3V}{42.91V} = 9.23
\]

Since \( n_{\text{total}} \) is an integer, \( n_{\text{total}} = 10 \). Then, at full-load, \( V_{dc} = 429.1 \)V.

Now consider the no-load operation. This fuel cell has a no-load voltage of \( V_{fc,NL} = 74.2 \)V; thus, at no-load, \( V_{dc,NL} = 742 \)V, that is an excess of 345.7V above the voltage needed for the dc-link of the inverter.

Normally, for a dc-link voltage of 396.2V, 600V inverter switches would be barely suitable; however, because of the high no-load voltages of the fuel-cells, in this case, 1200V switches are required.

An additional point for this case is that because of the variable dc-link voltage, the inverter control has to vary the modulation index by monitoring the dc-link voltage.

B. Case B

This case is similar to the configuration in Fig. 3 with multiple fuel cell modules in series replacing the single fuel cell module (Fig 5.). When ten fuel cell modules are used, the voltage supplied by the fuel cells is higher than what the dc-link needs; therefore, there is no need for boosting the voltage. In addition to this, since there is not much difference in the low voltage and high voltage portions of the circuit, the isolation is not essential. The most important role of this converter is to regulate the dc link voltage so it stays at 396.3 at all times.

Note that, in applications where less number of fuel cell modules are required, the dc-dc converter might have to buck and/or boost depending on the fuel cell output voltage, and isolation might be more important.

IV. LEVEL REDUCTION TECHNIQUE USING A CASCADED MULTILEVEL DC-DC CONVERTER

Residential applications and others, including hospitals, schools, apartment buildings etc. have a daily load profile with hours of full-load operation and hours of low-load operation. As explained earlier, when fuel cells are used, Case A requires ten fuel cells to maintain 396.3V for the dc-link. When the load is low, the dc link increases to 742V, which requires derating of the inverter devices.

One solution to limit the dc-link voltage is using Case B, which keeps it constant; however, the introduction of a dc-dc converter increases the cost without much of a benefit considering that isolation or voltage boost are not essential in this application.

Case B keeps the dc-link voltage constant so that the inverter switches are not necessarily derated; however, the dc-dc converter switches still have to be derated.

A better solution is the level reduction technique described in this paper. Level reduction is done by inhibiting fuel cells one by one when the load current decreases. Then, the voltage across the power switches is reduced, still maintaining the voltage and power required by the inverter and the load.

As an example, consider the no-load operation in Case A where ten fuel cells are operating no matter what the load current is. To generate 396.3V only \( 34.5V \) fuel cells would be sufficient; therefore, if four fuel cells are inhibited, then the dc-link voltage would be much less, 445.2V as opposed to 742V.

The number of levels required for any fuel cell voltage value can be calculated using

\[
    n > \frac{V_{dc}}{V_{fc,NL}} = \frac{396.3V}{74.2V} = 5.34
\]

\( n=6 \) fuel cells would be sufficient; therefore, if four fuel cells are inhibited, then the dc-link voltage would be much less, 445.2V as opposed to 742V.

The number of levels required for any fuel cell voltage value can be calculated using

\[
    n > \frac{V_{dc}}{V_{fc,NL}} = \frac{396.3V}{V_{fc,NL}} \tag{4}
\]

where \( n \) is an integer.

Using (4), the dc-link voltages for the level reduction technique and each of the other cases for the whole range of load currents are plotted in Fig. 6. As seen here, with level reduction, the maximum dc link voltage is around 450V compared to the 742V of Case A.

A. Case C

An ideal converter for the application of the level reduction technique is the cascaded multilevel dc-dc converter shown in Fig 7, which was originally introduced in [12-13] for a motor drive application.

Each fuel cell has an associated vertical (\( S_V \)) and a horizontal (\( S_H \)) switches. When \( S_H \) is on and \( S_V \) is off, the fuel cell supplies power to the load. On the other hand, if \( S_V \) is on and \( S_H \) is off, then the fuel cell does not supply any power; thus, it is inhibited.
Note that the level reduction technique is proposed for applications such as apartment buildings, schools, hospitals, etc. where the load varies throughout the day. However, the load variation is generally not fast; therefore, high frequency switching of the multilevel dc-dc converter is not a problem. Since this converter merely changes the dc voltage level when required, the control of the converter is rather simple.

A voltage sensor is required to monitor the fuel cell voltage; then, the controller can use (4) to calculate \( n \) and inhibit \((n_{\text{load}}-n)\) fuel cell modules.

In (4), all the fuel cells have been assumed identical. This technique would still work with all different fuel cells connected to the multilevel converter. The difference would be that the fuel cell with the least voltage would be inhibited first.

As seen in Fig. 7, a three-phase inverter is still required for the inversion. This inverter will require a variable modulation index to compensate for the varying dc-link voltage but this variation will not be as extreme as the one in Case A.

### B. Evaluation

1) **Power supplied**: For the same current value required by the inverter, the power supplied by the fuel cells for each case is calculated assuming 100% efficiency for the dc-dc converters and the results are plotted in Fig. 8. Since the dc-link voltage is kept constant in Case B, the power supplied is proportional to the load current. The difference between the curves in other cases and Case B is the excess power. As expected, Case A produces much more excess power for the same current than the other cases.

2) **Fuel Cell Utilization**: Fuel cell utilization in this paper is defined as the ratio of the power required by the inverter to the power supplied by the fuel cells for the same load current.

   \[
   F.C.U. \equiv \frac{P_{\text{required}}}{P_{\text{supplied}}} \forall \text{the same load current}
   \]  

   \[
   F.C.U. \equiv \frac{V_{dc} \cdot I}{V_{FC} \cdot I} = \frac{V_{dc}}{V_{FC}}
   \]

   For Case B, the fuel cell utilization is the same as the efficiency of the dc-dc converter, which is assumed to be 100%.

   Fig. 9 shows a plot of the fuel cell utilization for each case. As seen in this figure, Case B has the best fuel cell utilization and Case C has the worst. This conclusion, however, is deceptive since it is overlooking the point that in Case C, at any time there are up to four fuel cells idling. Factoring this fact in the fuel cell utilization, a modified fuel cell utilization can be defined as

   \[
   M.F.C.U. = F.C.U. \cdot \frac{n_{\text{total}}}{n}
   \]

   The extra term in (7) is one for Cases A and B at all current levels but varies between 1.67 (10/6) and 1 (10/10) for Case C. The resulting utilization plot is shown in Fig. 10 where it is
seen that the utilization in Case C is much higher than the utilization in the other cases at lower currents. Around full-load the utilization for Case C is similar to the utilization for the other two cases.

3) Comparison: Case A is the simplest configuration and has the minimum device count; however, the inverter switches have to be rated twice the dc-link voltage for full-load operation so that the system can operate at all loads.

Case B uses a dc-dc converter, so that the inverter switches do not have to be overrated; however, the dc-dc converter switches have to be rated higher. This converter also introduces bulky passive components and more expense.

Case C has two extra switches per fuel cell; therefore, the system has a higher component count but the additional expense is lower considering that the switches are of cheaper low voltage type. Another disadvantage is that there is always a switch per fuel cell in the load current path, no matter if the fuel cell is inhibited or not, causing extra conduction losses.

Case C also has the advantages of modularity and increased reliability with redundancy. This means that if a fuel cell fails, the system will continue to operate. The failing unit can be replaced as a module together with its switches in a short time decreasing the down time for repairs.

In Case C, for most of the load current range, there is one or more fuel cells that are idling. These can be used to charge batteries, etc. to increase the fuel cell utilization and the system efficiency. If using the idling fuel cells in other applications is not needed, the fuel cells can be left idle prolonging the life of the fuel cell. If the selection of fuel cells to be inhibited is rotated among all the existing fuel cells, the life expectancy of the whole system can be increased compared to the other cases.

V. CONCLUSIONS

A novel reduced level control technique for a cascaded multilevel DC-DC converter exploiting the V-I characteristics of fuel cells is introduced. With this control, the need for derating power semiconductors in fuel cell systems is eliminated. By inhibiting some of the fuel cells and using the inhibited fuel cells in other applications, like charging batteries, the system efficiency and the fuel cell utilization increase. If these fuel cells are left idling, then the life expectancy of the system increases. In addition to these, using the multilevel dc-dc converter also brings the advantages of modularity and increased reliability.

The level reduction technique is also applicable to other fuel cell-fed multilevel inverters.

REFERENCES