Multiple Input Converters for Fuel Cells

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Abstract— **Multilevel converters have been used previously to integrate several fuel cell modules for higher power applications. Some previous publications have also shown improvements in fuel cell utilization by exploiting the static characteristics of fuel cells which show more than a 30% difference in the output voltage between no-load to full-load conditions. This paper first describes standard fuel cell power electronics interfaces, then reviews a few of the multi input systems and explores additional configurations.**

I. Introduction

Fuel cell technology is one of the options for renewable energy sources [1,2]. The electrical efficiency of a fuel cell can be greater than 70% in theory (the present technology is 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_2O when H_2 is used as fuel, and no pollutants like SO_x or NO_x, are produced; therefore, the fuel cells are environmentally cleaner than traditional generators.

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 hotel might require a 200 kW power supply. To provide this power using the SOFC modules, 20 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 these converters 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 and a cascaded multilevel inverter are used to integrate several fuel cell modules. When recently developed level reduction technique [7, 8] is applied to these multilevel converters, fuel cell utilization is increased.

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II. Fuel Cell V-I Polarization Curve

The general V-I polarization curve for a single-cell fuel cell is shown in Figs. 1 and 2 where the reduction of the fuel cell voltage with load current density can be observed. This voltage reduction is caused by three major losses [9-11]. 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,

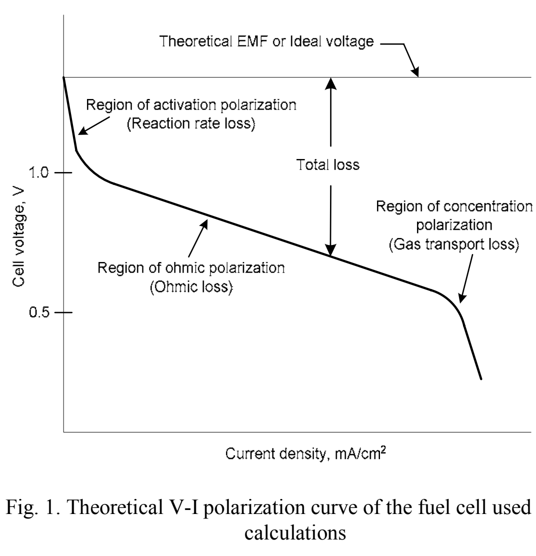

Fig. 1. Theoretical V-I polarization curve of the fuel cell used in the calculations

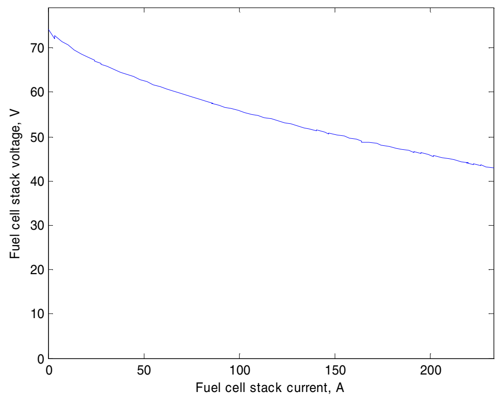

Fig. 2. Polarization curve for a 10kW solid oxide fuel cell module.

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 [12], 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 as is the case in practice. The resulting V-I curve in the figure shows a no-load voltage of $V_{fc,NL}$ = 74.2V and a full-load voltage, $V_{fc,FL}$ = 42.91V.

III. STANDARD FUEL CELL INTERFACE

Today, no standard rating exists for the output voltage of a fuel cell. Present fuel cells typically produce 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 [13]. The easiest and the most preferred approach would be the series configuration.

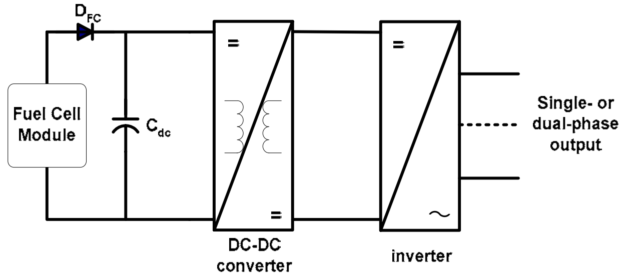

Fig. 3. Typical fuel cell power electronics interface block diagram.

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

$$n_{total} > \frac{V_{dc}}{V_{fc,FL}} \qquad (1)$$

where n_{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 $V_{fc,FL}$ = 42.91V (Fig 2), the number of fuel cell modules required to produce this dc voltage is

$$n_{total} > \frac{V_{dc}}{V_{fc,FL}} = \frac{396.3V}{42.91V} = 9.23 \qquad (2)$$

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

Now consider the no-load operation. This fuel cell has a no-load voltage of $V_{fc,NL}$=74.2V; thus, at no-load, $V_{dc,NL}$=742V, 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 396.3V, 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.

Ten of the fuel cell modules whose static characteristics are shown in Fig. 2 can produce 100kW of power and meet the

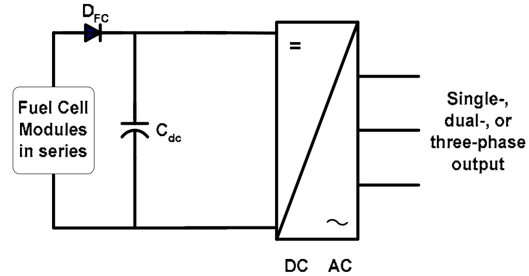

Fig. 4. Block diagram for Case A.

voltage requirement. To obtain 200kW, 20 fuel cells are required in ten parallel pairs. Caution must be taken to parallel fuel cells since circulating currents may arise when the instantaneous fuel cell voltages are not same. To avoid circulating currents, it is advised to insert diodes at the outputs of the fuel cells to prevent reverse flow of current.

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 put in series, 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 396.3V 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 several hours of full-load operation and several hours of low-load operation during each day. As explained earlier, when fuel cells are used, Case A requires ten fuel cells in series 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 might not be 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 [7, 8]. 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.

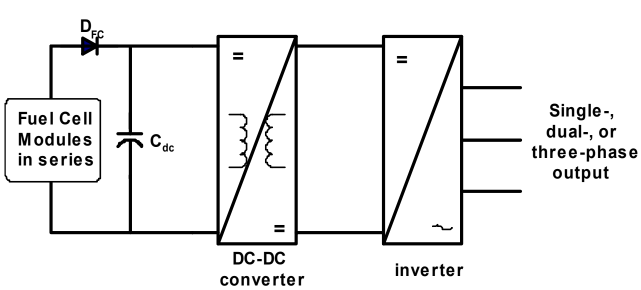

Fig. 5. Block diagram for Case B.

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

$$n > \frac{V_{dc}}{V_{fc,NL}} = \frac{396.3V}{74.2V} = 5.34 \quad (3)$$

n=6 fuel cells in series 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.

Notice that the combination of a multilevel dc-dc converter with several fuel cells enables the use of (3), which results in much fewer fuel cells required for a particular application than using (2). For the example in this paper, only 6 fuel cells would be sufficient as opposed to 10 without the multilevel dc-dc converter.

Fig. 6 shows the static characteristics of up to 10 fuel cells connected in series and how the level reduction technique works.

Plots of static characteristics of all the cases including level reduction for the whole range of load currents are plotted in Fig. 7. As seen here, with level reduction, the maximum dc link voltage is around 450V compared to the 742V of Case A.

A. Case C: Multilevel dc-dc Converter

An ideal converter for the application of the level reduction technique is the cascaded multilevel dc-dc converter shown in Fig. 8 which was originally introduced in [14, 15] for a motor drive application.

As introduced in [7], 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

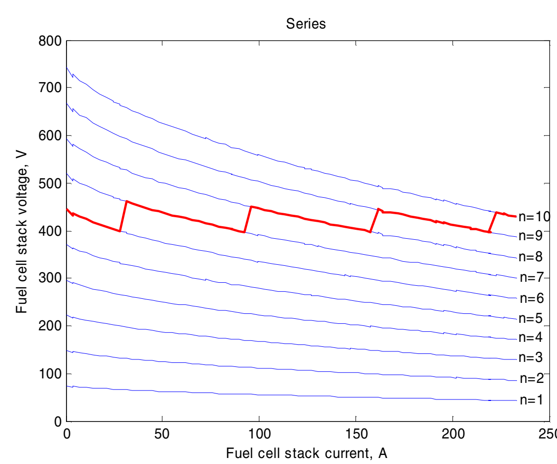

Fig. 6. Static characteristics for up to 10 fuel cells in series and level reduction technique.

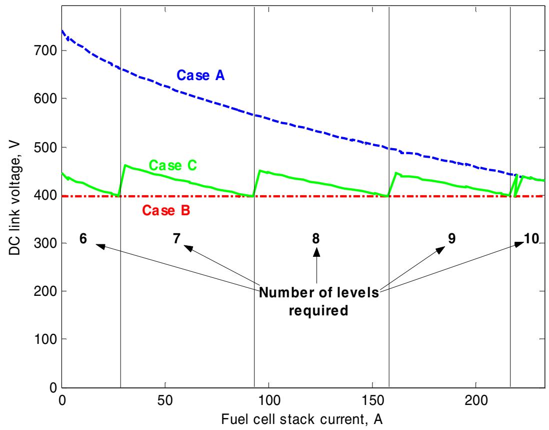

Fig. 7. Multilevel dc-dc converter output voltage for each case.

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 (3) to calculate n and inhibit (n_{total}-n) fuel cell modules.

In (3), all the fuel cells have been assumed identical. This technique would still work with fuel cells that produce different output voltages connected to the same multilevel converter. The difference would be that the fuel cell with the least voltage would be inhibited first.

As seen in Fig. 8, 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.

The comparison of all the three cases has already been given in [7].

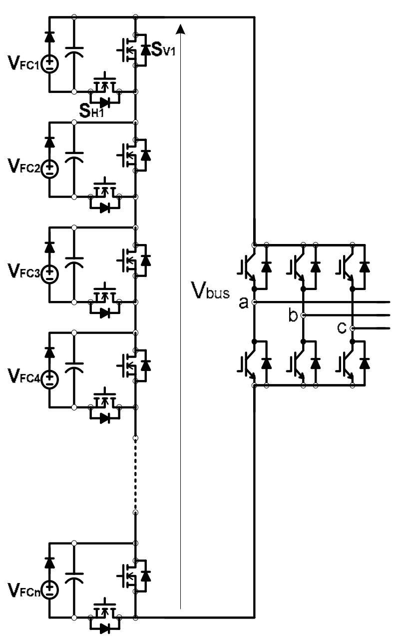

Fig. 8. Multilevel dc-dc converter connected to a three-phase inverter.

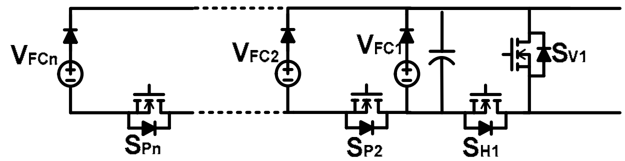

Fig. 9. Proposed parallel operation of fuel cells.

B. Parallel Operation

As mentioned in previous sections, for a 200kW operation, 10 fuel cell modules in series would satisfy the voltage constraint, but to achieve the power rating two modules have to be put in parallel before being connected in series.

This paper proposes an analogous parallel system to the multilevel dc-dc converter as shown in Fig. 9 to connect fuel cells in parallel. Each fuel cell comes with a series diode and a switch. The diode prevents from flowing into the fuel cell, and the switch isolates/inhibits the fuel cell if needed. As in the level reduction technique, different number of fuel cells can be inhibited to control the output voltage when the load decreases.

To demonstrate the operation of the proposed parallel fuel cell connection, Fig. 10, shows the static characteristics of up to five fuel cells connected in parallel. Assume that the system has to keep a 55V command output voltage at any current value. It can be observed in this figure that for a current range of 100-500A, this can be done with some error by inhibiting fuel cells when required. In the rest of the current spectrum, the error is much more; however, if the fuel cells are not switched in or out, the fuel cell output voltage would have been worse varying along the np = 5 fuel cell characteristics without any possibility of regulating the command voltage around a certain value. It can also be observed in the figure that for lower output voltage commands, the voltage can be controlled for a wider current range, the widest being for a voltage command of 42.91V, the minimum voltage a fuel cell can supply.

C. Parallel-Series (Matrix) Operation

In a multilevel dc-dc converter shown in Fig. 8, all the fuel cells can be replaced by parallel fuel cells shown in Fig. 9, producing a parallel-series or a matrix connection for high

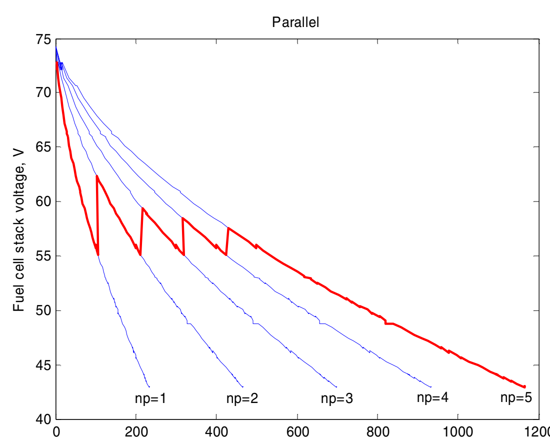

Fig. 10. Static characteristics for up to five fuel cells in parallel.

power applications. This increases the complexity of the control and introduces additional switch losses, but it should still be considered since present high power fuel cells are made up of conventional series and parallel connection of fuel cell stacks.

As an example, if a 500kW application is considered, then Figs. 6 and 10 can be combined to demonstrate what happens if 10 parallel strings of five fuel cells are connected in series in a multilevel dc-dc converter configuration. Fig. 11 shows what the static characteristics of this combination would look like. Notice that the dotted (green) line shows the output voltage of 10 fuel cells with level reduction without the proposed parallel operation. The thick solid (red) line, however, shows the output voltage closer to the setpoint of 396.1V with the proposed parallel operation.

Even though the output voltage is closer to the command value with the newly introduced technique, the gain for most applications is minimal considering the higher losses and higher cost introduced by the additional switches.

V. Level Reduction Technique Using Cascaded Multilevel Inverters

As an alternative to the dc-dc converter configuration, [8] has focused on a cascaded multilevel inverter. The advantage of this configuration compared to the earlier one is that all the switches of the multilevel inverter configuration will have low voltage ratings unlike the higher voltage ratings of the inverter switches in [7]. However, a disadvantage is that there will be two switches conducting the load current for each fuel cell compared to one in [7]. These two switches reduce the efficiency of the system because of the additional conduction losses; therefore, it is not wise to use a multilevel inverter system for low voltage fuel cells but should rather be considered for higher voltage fuel-cells.

For a multilevel inverter to operate at fundamental switching frequency, the switching angles should be carefully selected so that the total harmonic distortion (THD) is reduced. Solutions for angles for inverters with different number of levels have been presented in the literature [16]. These angles are stored in look-up tables with respect to the

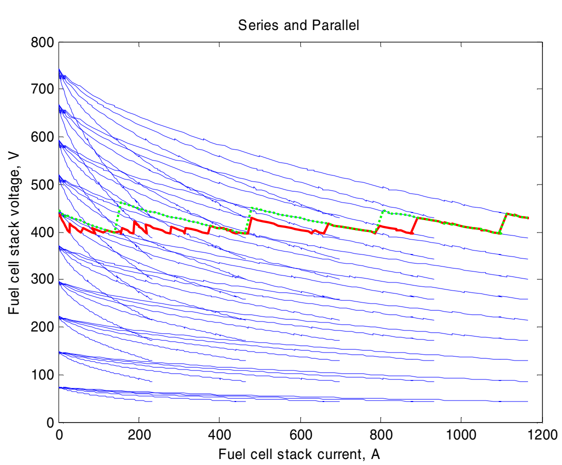

Fig. 11. Static characteristics for up to five fuel cells in parallel and up to ten in series.

modulation indices. For a reduced level multilevel inverter, several sets of these angles have to be stored, and an algorithm has to be developed to determine when to reduce the levels, which increases the control complexity.

A multilevel fundamental frequency sine-triangle wave comparison technique inspired from multilevel PWM [17-23] is introduced to simplify the control system. Fig. 12 shows the modulating waveform and the carrier waveforms for a 7-level (3-fuel cell) system. Because there are three converters available, three carrier waves are required, one for each converter. These carrier waves are (V_c /3) peak-to-peak and (V_c /3) offset from each other where V_c is equivalent to the peak of the carrier wave in sinusoidal PWM for a single converter. For an n-converter system, the carrier waves would be (V_c /n) peak-to-peak and (V_c /n) offset from each other.

As can be observed from Fig. 12, if the amplitude of the modulating wave is greater than (2 V_c /3), no H-bridges are inhibited. If it is between (2 V_c /3) and (V_c /3), then one inverter is inhibited; and if it is less than (V_c /3), two inverters are inhibited.

The modulation index for a multilevel inverter is defined as $m_a \equiv V_1/(n \cdot 4 \cdot V_{dc}/\pi)$, where n is the number of levels and V_{dc} is the voltage input to each H-bridge.

The modulation index of a n-level inverter depends on two variables, the dc input (fuel cell output) voltage and the output fundamental voltage. For a constant fundamental output voltage, if the dc input voltage increases, then m_a needs to decrease. The voltage in a fuel cell system will increase in low load conditions; therefore, the modulation index will decrease. In Fig. 12, it can be seen that as the modulation index is decreased, it will miss some of the carrier waves; therefore, the number of levels will be reduced automatically. The level reduction is simulated for a 6 fuel cell multilevel inverter and the transition from high-to-low load or from 13 levels to 11-levels is illustrated in Fig. 13.

Since a simple sine-triangle comparison at fundamental frequency is being used instead of switching angle optimization techniques, total harmonic distortion (THD) might be a concern. Fig. 14 shows the THD of the output voltage waveform when level reduction control with sine-triangle comparison is used. Note that for the calculation, harmonics up to and including the 41st order harmonic are used and the triplen harmonics are ignored. The plot shows that, as expected, THD decreases at higher modulation indices, i.e. when more levels are present. It must be noted that this is

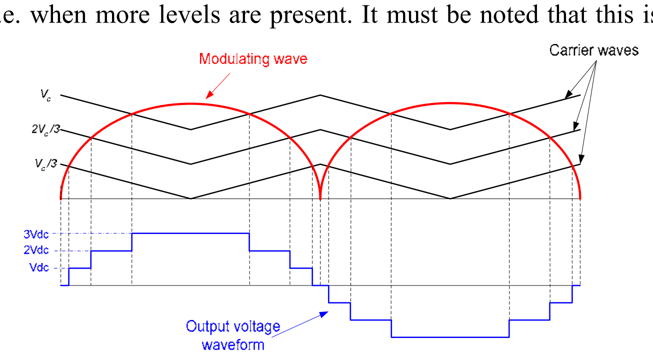

Fig. 12. Fundamental switching sine triangle wave comparison.

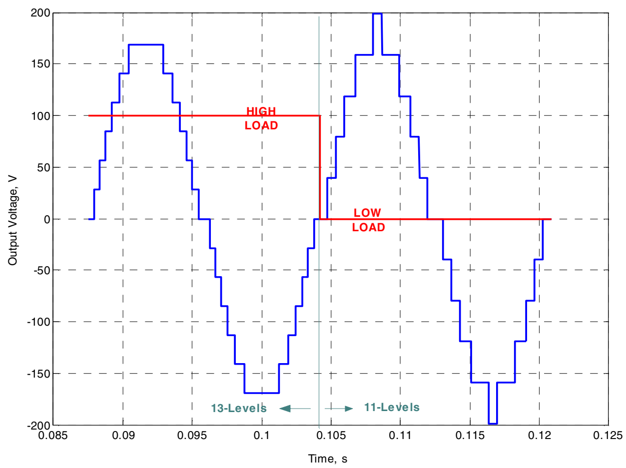

Fig. 13. Output voltage waveform simulated for high-load to low-load transition.

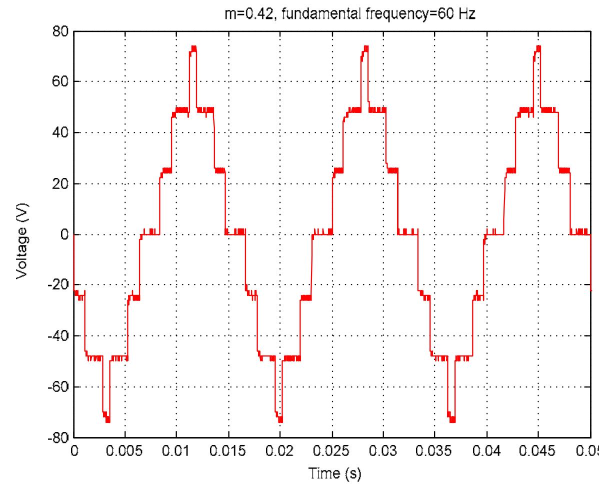

Fig. 15. 7-level output voltage waveform for low fuel cell load.

the THD for the unfiltered voltage waveform. If a further reduction in THD is required, then the frequency of the carrier wave can be increased for low frequency PWM operation.

VI. Experimental Results

The control algorithm has been tested on a 10kW cascaded multilevel inverter. Since no fuel cells were available in the lab, possible fuel cell characteristics were simulated and the multilevel inverter was operated in two conditions: low load and full load. At low loads, the fuel cell voltage increases and consequently the modulation index decreases. In this case, for a modulation index of 0.42, seven levels are enough to produce the required fundamental output voltage as shown in Figs. 15 and 16.

For higher loads, the fuel cell voltage decreases and the modulation index increases. For a modulation index of 0.85, the number of required levels increases to 11 as shown in Figs. 17 and 18.

THD values of up to 41st harmonic in both cases are given as 17.3% for m_a=0.42 and 7.12% for m_a=0.85. As expected for lower modulation index, the THD is worse. To improve the THD of the output voltage waveforms, a filter could be employed. Another alternative is to increase the frequency of the carrier wave so that the output waveform will be more like a low frequency multilevel PWM voltage.

VII. Conclusions

Novel multiple input converter topologies for fuel cells have been reviewed. With reduced level control technique exploiting the V-I characteristics of fuel cells, 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 a multilevel converter also brings the advantages of modularity and increased reliability.

For the multilevel inverter, a fundamental switching sine-triangle comparison method is introduced. This method decreases the complexity of the level reduction control for the

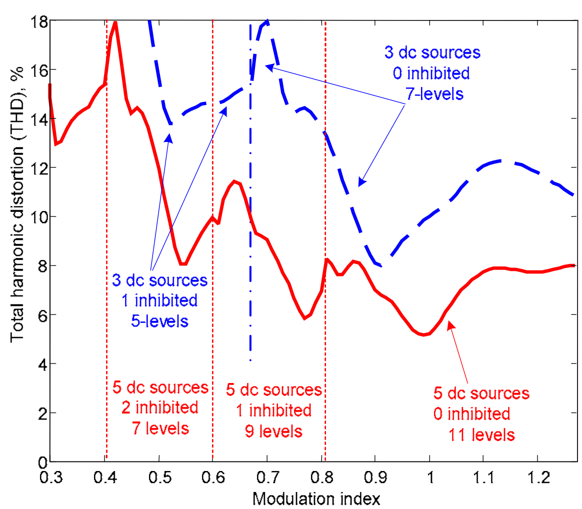

Fig. 14. Total harmonic distortion with respect to the modulation index.

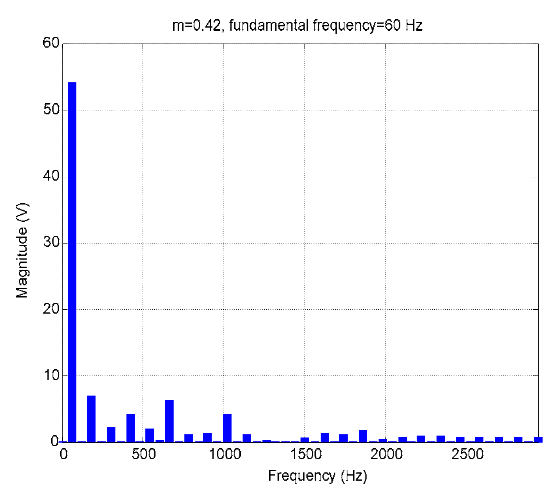

Fig. 16. FFT of the voltage waveform in Fig. 15.

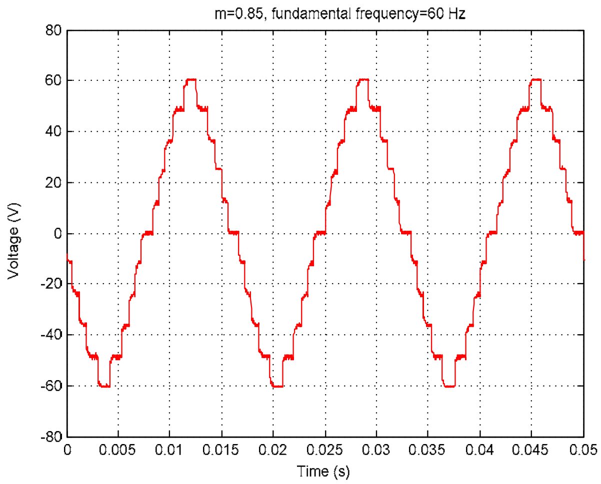

Fig. 17. 11-level output voltage waveform for high fuel cell load.

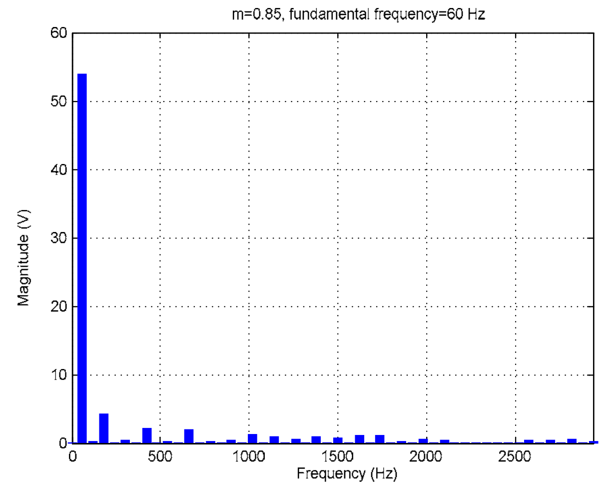

Fig. 18. FFT of the voltage waveform in Fig. 17.

multilevel inverters by eliminating the need for storing separate switching angle look-up tables for multilevel inverters for each number of dc sources.

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

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