Optimum Fuel Cell Utilization with Multilevel Inverters

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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 inverter. 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.**

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_x, CO_2 and SO_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 present technology is capable of reaching around 45% efficiency). 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 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.

Prepared by the Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, managed by UT-Battelle for the U.S. Department of Energy under contract DE-AC05-00OR22725.

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 inverter 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 inverter.

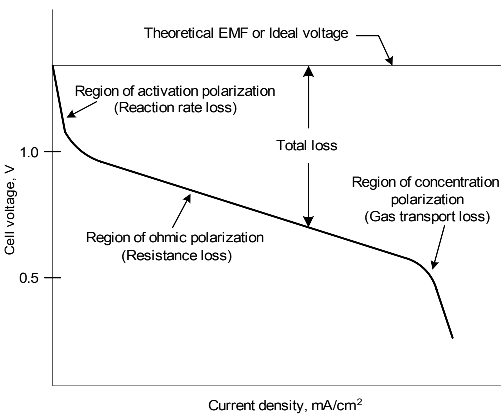

Fig. 1. Theoretical V-I polarization curve of the fuel cell used in the calculations.

II. General 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 [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.

III. Cascaded Multilevel Converters

The cascaded multilevel converter is one of several multilevel configurations. It is formed by connecting more than one single-phase H-bridge converter in series as shown in Fig. 3. Each converter generates a square wave voltage waveform with different duty ratios, which together form the output voltage waveform as in Fig. 4. A three-phase configuration can be obtained by connecting three of these converters in Fig. 3 in wye or delta. Instead of square waves, it is also possible to get PWM output voltages; however, in this paper, fundamental frequency switching will be emphasized instead of high frequency PWM switching.

IV. Level Reduction Technique

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. A dc-dc boost converter is generally 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.

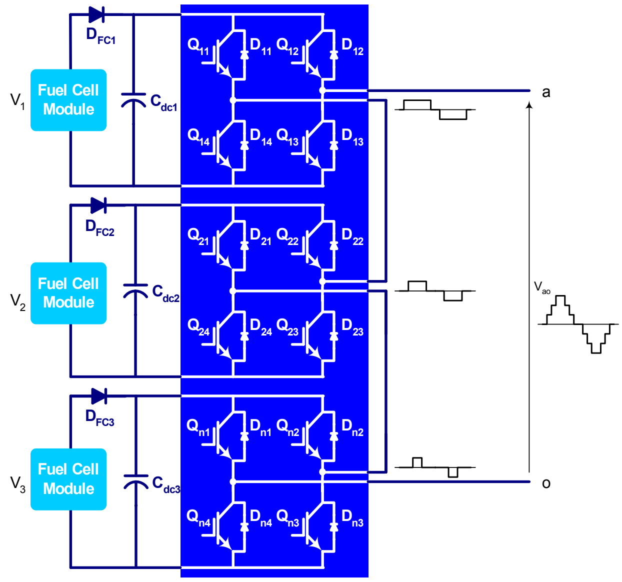

Fig. 3. 7-level cascaded multilevel inverter.

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. The application will be designed for full-load conditions; however, during low load operation, because of the load dependent characteristics of the fuel cells, the fuel cell voltage can be up to 50% more than the full-load case. This increase in the voltage requires derating of the inverter devices.

The dc-dc boost converter keeps the dc-link constant so

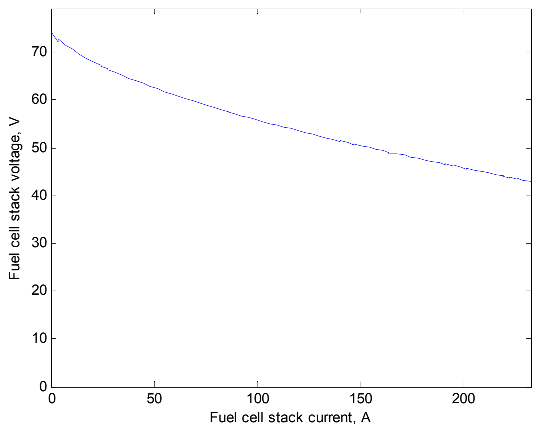

Fig. 2. Polarization curve for a 10kW solid oxide fuel cell module [10].

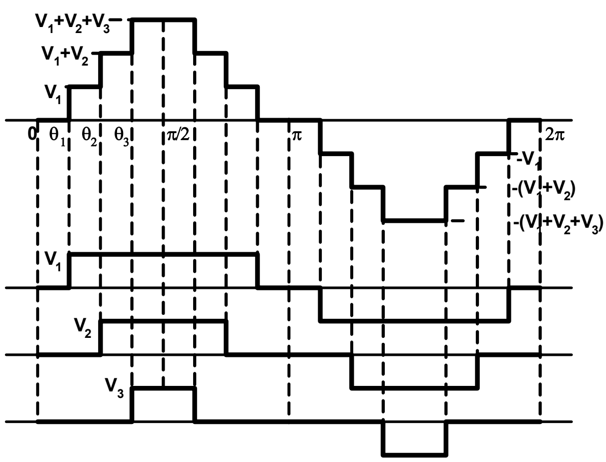

Fig. 4. n-level cascaded multilevel inverter waveform generation.

that the inverter switches are not necessarily derated; however, the dc-dc converter switches still have to be derated. It also increases the cost without much of a benefit considering that isolation or voltage boost might not be essential in this application.

A better solution is the level reduction technique described in [11] using a multilevel dc-dc converter supplying power to a three-phase inverter. Level reduction is done by inhibiting fuel cells one by one when the load current decreases. Then, the voltage across the inverter switches is reduced, still maintaining the voltage and power required by the inverter and the load.

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.

V. Cascaded Multilevel Inverters

As an alternative to the dc-dc converter configuration, this paper focuses 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 [11]. However, a disadvantage is that there will be two switches conducting the load current for each fuel cell compared to one in [11]. 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.

VI. Level Reduction Control

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 [12]. These angles are stored in look-up tables with respect to the 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.

In this paper, a multilevel fundamental frequency sine-triangle wave comparison technique inspired from multilevel PWM [13-19] is introduced to simplify the control system. Fig. 5 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

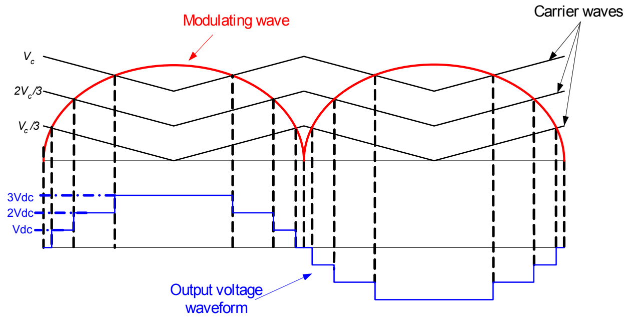

Fig. 5. Fundamental switching sine triangle wave comparison.

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. 5, 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) V 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. Fig. 6 shows the input-output relationship of a 13-level inverter for the fundamental frequency sine-triangle comparison system. For each m_a in the x-axis, the y-axis shows the scaling factor that gives the peak output voltage when multiplied by V_{dc}. This relationship is not linear for any m_a as would have been expected when compared with other similar modulation techniques.

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. Fig. 6 shows that as the modulation index decreases, the 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. 7.

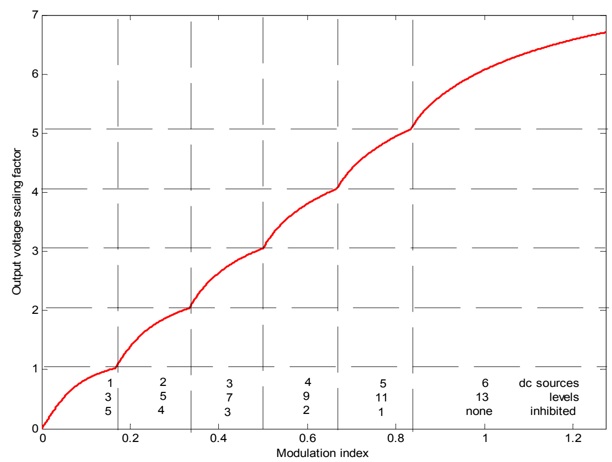

Fig. 6. Modulation index correction plot.

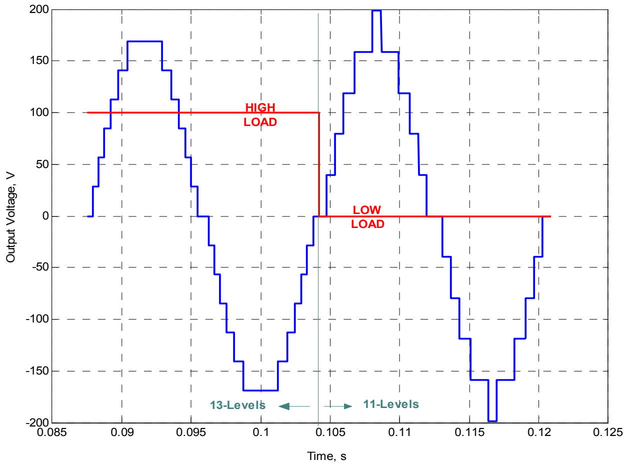

Fig. 7. Output voltage waveform simulated for high-load to low-load transition.

The inhibited H-bridges and fuel cells can be used to charge batteries to increase the efficiency and the utilization of the fuel cells further. Moreover, since the lifetime of a fuel cell is generally given in operating hours, by alternating the inhibited fuel cell(s), the operating lifetime of the fuel cell can also be extended.

Since a simple sine-triangle comparison is being used instead of switching angle optimization techniques, total harmonic distortion (THD) might be a concern. Fig. 8 shows the THD of values 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 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.

VII. 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 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. 9 and 10.

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 go up to eleven as shown in Figs. 11 and 12.

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.

VIII. Conclusions

A novel reduced level control technique for multilevel inverters 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 H-bridges, the fuel cell utilization is increased. The fuel cells in the inhibited H-bridges can be used to charge batteries, increasing the system efficiency.

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

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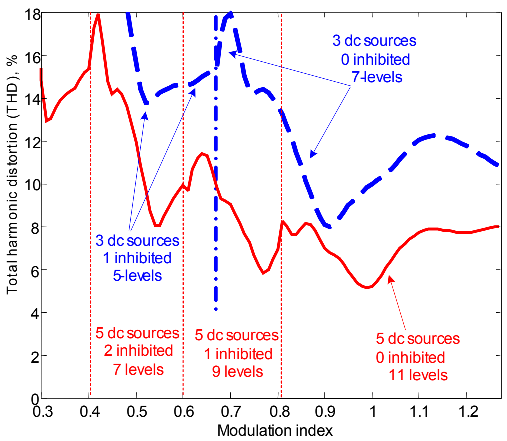

Fig. 8. Total harmonic distortion with respect to the modulation index.

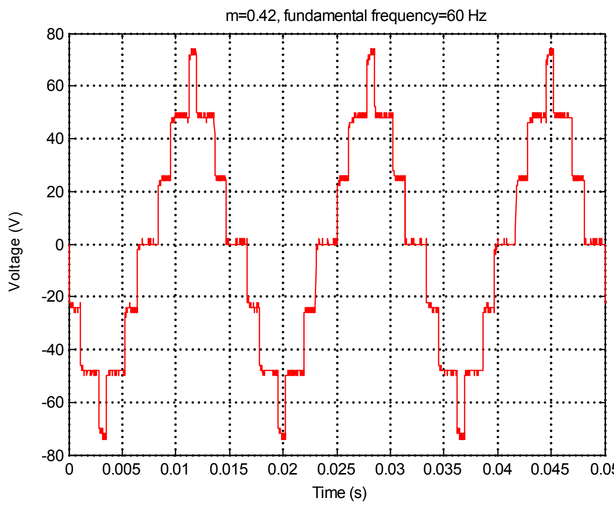

Fig. 9. 7-level output voltage waveform for low fuel cell load.

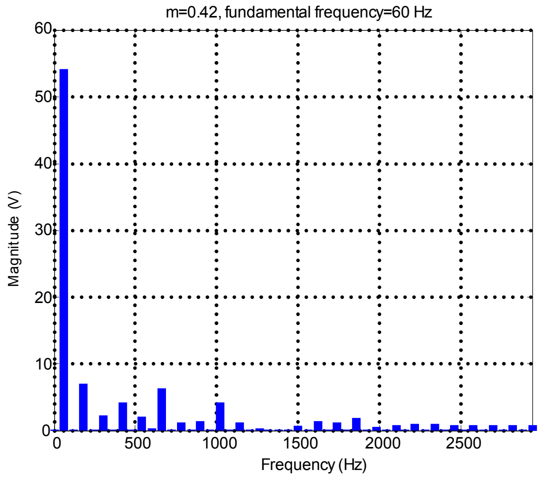

Fig. 10. FFT of the voltage waveform in Fig. 9.

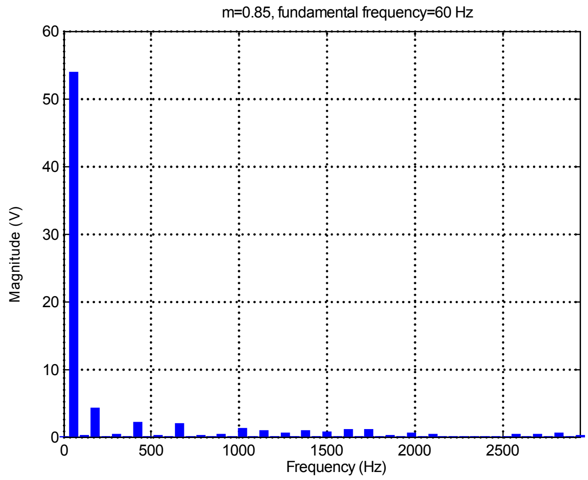

Fig. 12. FFT of the voltage waveform in Fig. 11.

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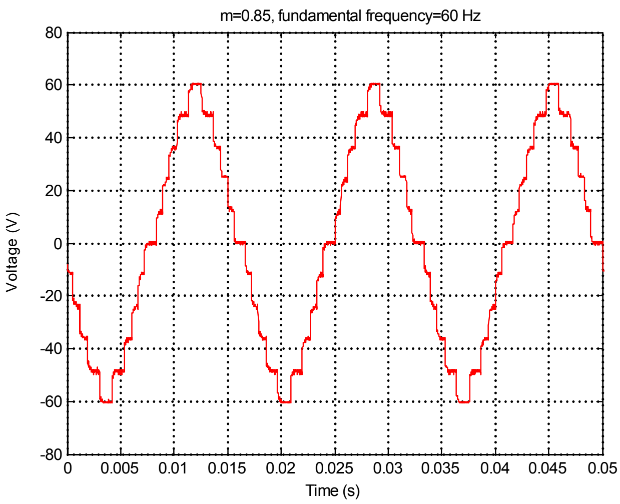

Fig. 11. 11-level output voltage waveform for high fuel cell load.