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CASCADED FUEL CELL STACK MULTILEVEL INVERTER USED FOR MINIMIZATION OF TOTAL HARMONICS DISTORTION

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Abstract:

Multilevel inverter is one of the promising technologies for alternative source of power generation to generate waveforms close to a sinusoid. Among the multilevel inverter topologies, cascaded multilevel inverter requires the least number of switches and DC sources. The main objective of this work is to develop an Matlab simulation model of the fuel cell stack based a cascade multilevel inverter. The fuel cell stack and reformer model is simulated using Matlab and the fifteen level inverter output is verified using fuel cell as the power source. The output power flow of fuel cell stack system is controlled by PID controller.

Key words: Cascaded Multilevel Inverter, PWM(pulse width modulation) technique, THD(Total Harmonic Distortion) , PEM (proton exchange membrane).

1. Introduction

In many applications have begun to require higher power apparatus in recent years. Some medium voltage motor drives and utility applications require medium voltage and megawatt power level. For a medium voltage grid, it is troublesome to connect only one power semiconductor switch directly. As a result, a multilevel power converter structure has been introduced as an alternative in high power and medium voltage situations. A multilevel converter not only achieves high power ratings, but also enables the use of renewable energy sources. The concept of multilevel converters has been introduced since 1975. The term multilevel began with the three-level converter. Subsequently, several multilevel converter topologies have been developed.

1.1 Multi Level Inverter

A multilevel inverter is a power electronic system that synthesizes a sinusoidal voltage output from several DC sources. These DC sources can be fuel cells, solar cells, ultra capacitors, etc. The main idea of multilevel inverters is to have a better sinusoidal voltage and current in the output by using switches in series. Since many switches are put in series the switching angles are important in the multilevel inverters because all of the switches should be switched in such a way that the output voltage and current have low harmonic distortion.

Pure electric cars have demerits such as a short driving distance, long recharging time, and high cost. Thus, fuel cell vehicles (FCV), which have a longer distance and higher transportation capability than pure electric cars. FCV is one type of electric vehicles with fuel cell system which is the main generating unit. Electric vehicles require batteries as the energy source. Batteries need to be recharged after electric vehicles operate for a few hours[1]. A hydrogen-based, fuel cell provides the power to give an electric vehicle the same range as a gasoline powered vehicle. In this case, a fuel cell stack generates the electricity by combination of hydrogen and oxygen. [2] The products of the electrochemical process are electricity, heat and water. Polymer Electrolyte Membrane Fuel Cell (PEM Fuel Cell) is popular and suitable used in vehicles. It operates within a range of relatively low temperatures, has higher efficiency than combustion engines, is very quiet and produces no emissions. [3].

2. About Fuel cell Stack

A fuel cell converts the chemicals hydrogen and oxygen into water, and in the process it produces electricity. Most fuel cells in use today use hydrogen and oxygen as the chemicals. A fuel cell is an electrochemical energy conversion device. The proton exchange membrane fuel cell (PEMFC) is one of the most promising technologies. This is the type of fuel cell that will end up powering cars, buses and maybe even your house. The PEMFC uses one of the simplest reactions of any fuel cell.

- The anode is the negative post of the fuel cell conducts the electrons that are freed from the hydrogen molecules so that they can be used in an external circuit.
- The cathode is the positive post of the fuel cell, has channels etched into it that distribute the oxygen to the surface of the catalyst and form water.

- The electrolyte is the proton exchange membrane looks something like ordinary kitchen plastic wrap, only conducts positively charged ions. The membrane blocks electrons.

The open circuit voltage calculation is based on the Nernst equation having the following form:

$$V_{oc} = V_{oc}^{o} + \frac{RT}{2F} ln \left[\frac{\frac{P_{H2}}{P^{o}}\left(\frac{P_{O2}}{P^{o}}\right)^{1/2}}{\frac{P_{H2O}}{P_{H2O}^{o}}} \right] \quad (1)$$

Where V_{oc}^{o} is the open circuit voltage at standard pressure P^{o} and temperature T, R is the molar gas constant, F is the Faraday constant, P_{H2}, P_{O2} and P_{H2O} are partial pressures of hydrogen, oxygen and water vapor respectively and P_{H2O}^{o} is the saturation pressure of water at the temperature T.

The cells' peak power is 14.25 kW per sub-stack, and 85.5kW total .Fuel cell efficiencies vary between 50 percent at 0.6V/cell and 67 percent at 0.8V/cell. Specific energy is dependent on the quantity of hydrogen available to feed the fuel cell. Current density is 0.94A/cm at 0.6V/cell.

The open circuit voltage at standard pressure is calculated as follows.

$$V_{OC}^{o} = \frac{-g_f}{2F} \quad (2)$$

Where g_f is the Gibbs free energy of formation reaction for the fuel cell.

The chemical reactions in the PEM fuel cell can be described as follows

Anode: 2H2→4H++4e-
Cathode: O_2+4H^++4e^-→2H_2O (3)
Overall: 2H_2+ O_2→2H_2O

The operational voltage V_{fc} is calculated by subtracting from the open circuit voltage of the equation (2) the losses associated with operating conditions. These losses are the ohmic losses ΔV_{ohm} due to electric and ohmic resistance, the activation losses ΔV_{act} associated with driving the chemical reaction and the mass transportation losses ΔV_{mass} caused by the changes in concentration of the reactants and products. The losses are calculated as given in eqn.(4),(5) and (6).

$$\Delta V_{ohm} = i * f_f \quad (4)$$

$$\Delta V_{act} = A_f in(i/i_o) \quad (5)$$

$$\Delta V_{Mass} = m * m^{ni} \quad (6)$$

Where, i is the current density. The values of the constants used in the calculations are summarized in table 7 [14]. Using the equations above the operational voltage can be calculated according to:

$$V_{fc} = V_{oc} - \Delta V_{ohm} - \Delta V_{act} - \Delta V_{mass} \quad (7)$$

$$V_{fc} = V_{oc} - ir_f - A_f \ln(i/i_o) - me^{nt} \quad (8)$$

$$V_{fc} = \frac{-g_f}{2F} + \frac{RT}{2F} \ln \left(\frac{\frac{P_{H2}}{P^{o}}\left(\frac{P_{O2}}{P^{o}}\right)^{\frac{1}{2}}}{\frac{P_{H2O}}{P_{H2O}^{o}}} \right) + A_f \ln(i_0) - ir_f - A_f \ln(i) - me^{ni} \quad (9).$$

Using the form of an equation (9) it is possible to adapt the operational voltage calculation to the results of experimental measurements on a specific fuel cell. In this study literature data are used, since such experiments are not performed. Figure 1 shows the cell voltage as a function of current for the fuel cell used in the model.

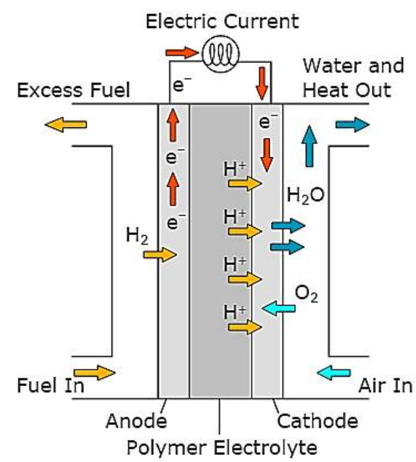

Fig.1 Fuel Cell Model

This reaction in a single fuel cell produces only about 0.7 volts. To get this voltage up to a reasonable level, many separate fuel cells must be combined to form a fuel-cell stack.

3. DC-DC Converter

The DC to DC converter is voltage-regulated system as shown in fig. 2. The DC/DC converter adapts the low voltage of the battery (200 V) to the DC bus which feeds the AC motor. A

DC-DC converter is a device that accepts a DC input and produces a DC output voltage. It would be step-down (Bust) converter to lower input voltage or step-up (Boost) converter to increase input voltage.

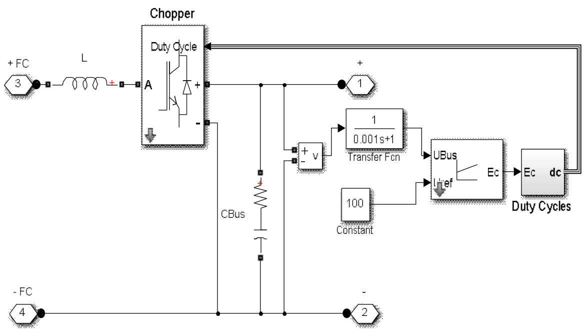

Fig.2 DC to DC Boost Converter

3.1Multilevel Inverter

The multilevel converter is one of the more promising techniques for mitigating the aforementioned problems. Multilevel converters utilize several DC voltages to synthesize a desired AC voltage.

One application for multilevel converters is distributed power systems. Multilevel converters can be implemented using distributed energy resources such as photovoltaic and fuel cells, and then be connected to an AC power grid. If a multilevel converter is made to either draw or supply purely reactive power, then the multilevel converter can be used as a reactive power compensator. For example, a multilevel converter being used as a reactive power compensator could be placed in parallel with a load connected to an AC system. This is because a reactive power compensator can help to improve the power factor of a load [14].

3.2 H-Bridge Inverter:

The control of cascaded H-bridge structure is simple, and this structure does not has DC voltage-equalizing problems as shown in fig. 3. So the cascaded H-bridge structure is widely used in large-capacity high-voltage power electronic devices.

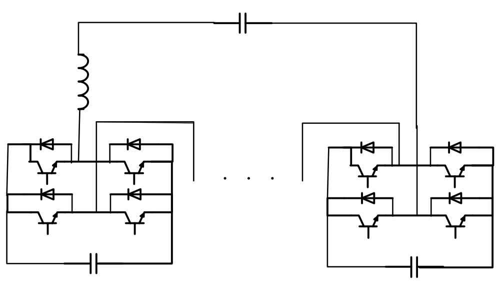

Fig.3 Diagram of cascaded H-bridge

4. Topology of Multilevel Converters

4.1. Diode-Clamped Converter

The simplest diode-clamped converter is commonly known as the neutral point clamped converter (NPC) which was introduced by Nabaeet al. [4] as shown in fig. 5. The NPC consists of two pairs of series switches (upper and lower) in parallel with two series capacitors where the anode of the upper diode is connected to the midpoint (neutral) of the capacitors and its cathode to the midpoint of the upper pair of switches; the cathode of the lower diode is connected to the midpoint of the capacitors and divides the main DC voltage into smaller voltages, which is shown in Figure 4. In this example, the main DC voltage is divided into two. If the point O is taken as the ground reference, the three possible phase voltage outputs are -1/2 V_{dc} , 0, or 1/2 V_{dc} . The line-line voltages of two legs with the capacitors are: V_{dc} , 1/2 V_{dc} , 0, -1/2 V_{dc} .

4.2. Capacitor-Clamped Converter

The capacitor-clamped multilevel converter or flying-capacitor converter [6], [12] is similar to the diode-clamped topology. However, the capacitor-clamped multilevel topology allows more flexibility in waveform synthesis and balancing voltage across the clamped capacitors. For a three-level capacitor-clamped multilevel converter, if the *O* point is taken as the ground reference, a single phase can produce three output levels (-1/2 V_{dc}, 0 and 1/2 V_{dc}). The general m -level capacitor-clamped multilevel converter has an *m*-level output phase voltage. Similar to the diode-clamped multilevel converter, the capacitors have different ratings. These capacitors result in a bulky, and expensive converter when compared to the diode-clamped converter. The configuration has mixed-level hybrid multilevel units because it embeds multilevel cells as the building block of the cascade converter.

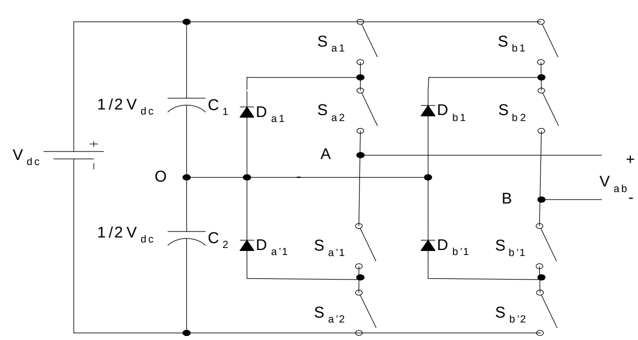

Fig.4 Neutral point diode-clamped converter

4.3. Selective Harmonic Elimination

The popular selective harmonic elimination method is also called a fundamental switching frequency method which is based on the harmonic elimination theory developed by Patel *et al* [28][29]. By applying Fourier series analysis, the output voltage can be expressed as

$$V(t)=\sum_{n=1,3,5...}^{\infty}\frac{4}{n\pi}(V_1\cos(n\theta_1)+V_2\cos(n\theta_2)+...+V_s\cos(n\theta_s))\sin(n\omega t) \quad (10)$$

Where, s is the number of DC sources, and V_1, V_2 ... V_s are the level of DC voltages. The switching angles must satisfy the condition $0<\theta_1<\theta_2<\cdots<\theta_s<\frac{\pi}{2}$.

However, if the switching angles do not satisfy the condition, this method no longer exists. If, $V_1=V_2=...=V_s$, this is called an equal DC voltages case. To minimize harmonic distortion and to achieve adjustable amplitude of the fundamental component, up to s-1 harmonic contents can be removed from the voltage waveform. In general, the most significant low-frequency harmonics are chosen for elimination by properly selecting angles among different level converters, and high-frequency harmonic components can be readily removed by using additional filter circuits. To keep the number of eliminating harmonics at a constant level, all switching angles must satisfy the condition $0<\theta_1<\theta_2<\cdots<\theta_s<\frac{\pi}{2}$, or the total harmonic distortion (THD) increases dramatically. Due to this reason, this modulation strategy basically provides a narrow range of modulation index, which is one of its disadvantages [13].

Therefore, the modulation control problem is converted into a mathematical problem to solve the following equations for a three-phase system. Here, *m* is modulation index.

$$\begin{gathered}V_1\cos(\theta_1)\pm V_2\cos(\theta_2)\pm V_3\cos(\theta_3)\pm...\pm V_s\cos(\theta_s)=m\\ V_1\cos(5\theta_1)\pm V_2\cos(5\theta_2)\pm V_3\cos(5\theta_3)\pm...\pm V_s\cos(5\theta_s)=0\\ \vdots\\ V_1\cos(n\theta_1)\pm V_2\cos(n\theta_2)\pm V_3\cos(n\theta_3)\pm...\pm V_s\cos(n\theta_s)=0\end{gathered}$$

(11)

5. Model Description

Here in the model the fuel cell stacks are cascaded to maintain the voltage level up to the requirement. There are three segments are arranged so that the three phase power can be generated. First of all the fuel cell generated dc voltages is step-up by using dc-dc boost converter and then it is converted to ac voltage by using H-Bridge inverter. Basically model has divided into three major parts named as: Fuel cell, dc-dc boost converter and H-Bridge inverter. In the proposed work five fuel cell stacks are cascaded for single phase, so that the gain is to be made up to the required limit, in the same way for all the remaining phases it is done as shown in fig.5.

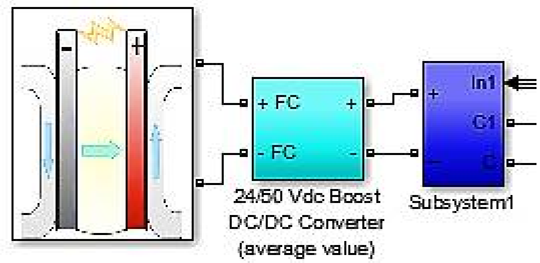

Fig.5 Proposed Model Block Diagram

The dc to dc boost converter is designed such a way that the voltage level can be lifted up to the required limit by optimal switching, generated by the PWM generation sub-system. Now this lifted dc voltage is inverted into ac with eleven levels by inverter. Another important part or subsystem of the complete system is present to generate switching pulse train for dc-dc boost converter and inverter.

6. Simulation Results

The high multilevel output approaches the sinusoidal signal and the THD value reduced. Here the response of the first part is shown, which is actually designed to generate the pulse train for switching the inverter IGBTS. Each and every pulse is of about .08 sec.

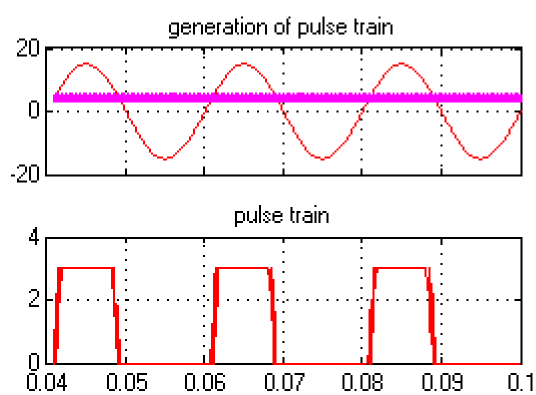

Fig.6 Generation of Pulse Train

The pulse train is for all the five inverters used in the phase A, B or C identically is shown in the figure (7). Pulse train is generated with the help of PWM generator. Every pulse is dedicated to the corresponding converter existing in the cascaded form.

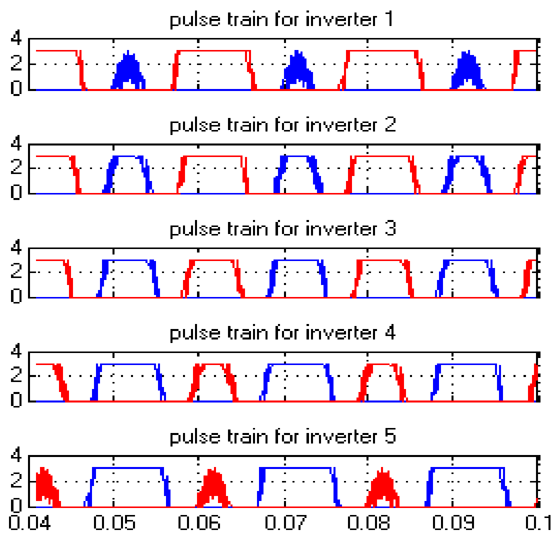

Fig.7 Pulse Train to the Inverter

In figure 8 combined three phase output voltage waveforms are shown, this is the output, which is the individual response of all the three subparts of the system. The three phase output is in proper in phase, which is done with the proper switching, only the distortion is present within it.

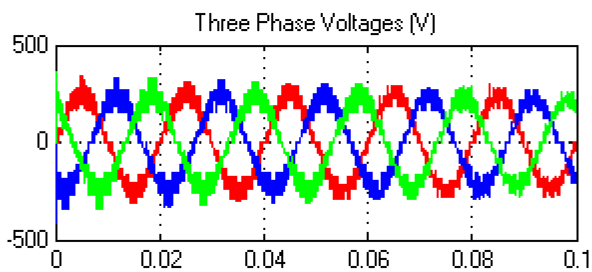

Fig.8 Combined Phase waveform without improvement

As per the waveform conditioning sub-system the distorted output is improved, in fig 9 blue color waveform shows the unconditioned output voltage while as red color waveform shows the conditioned output voltage.

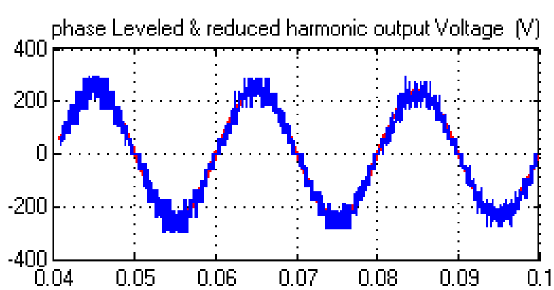

Fig. 9 Actual and improved output voltage waveforms

In figure 10 the improved output voltage is shown below, here we can see that the output voltage is more proper and the quality of the output is measured in the form of THD value. So it is most accurate, high level output voltage.

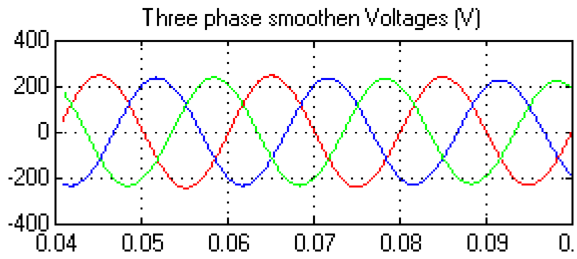

Fig.10 Combined improved output voltage waveforms

In case, as the improvement is done the output voltage is improved and THD is found .95% of the fundamental. The THD value is minimized up to a great extent with the reduction of higher order harmonics as shown in FFT window in figure (11).

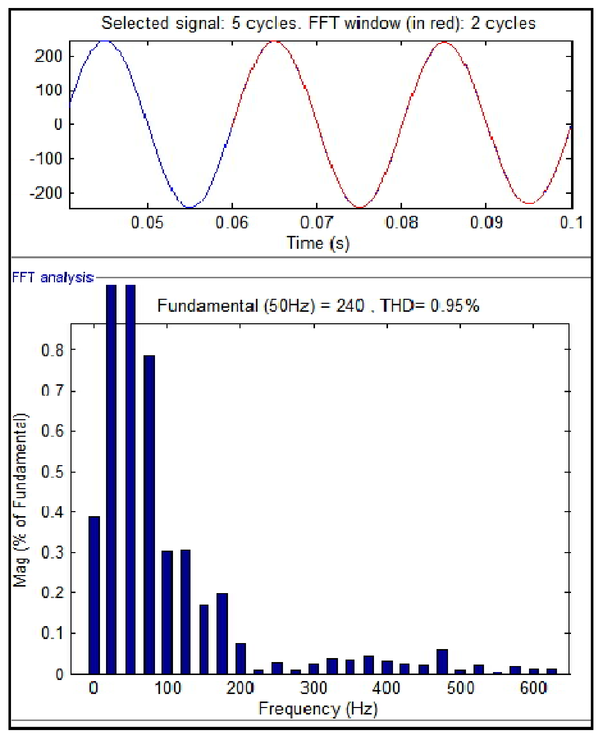

Fig.11 FFT analysis of Improved output voltage waveforms

The FFT window shown in figure (11), we can see that the even and odd level harmonics are minimized as compare to the above.

Conclusions

Recently trend of modulation control for multilevel converters is to output is high quality power with high efficiency. For this reason, popular traditional PWM, sinusoidal PWM (SPWM) methods and space vector PWM (SVPWM) methods are not the best methods for multilevel converter control due to their high switching frequency. The resultant method can solve low order harmonic equations, but cannot solve high order harmonic equations. In this work, switching angles for each H-Bridge converter are equal. If the switching angle numbers for each H-Bridge converter are not equal, it may be possible to find more solutions for a wider modulation index range. Here in the proposed work the signal improvement is done to make the output signal proper. The THD is reduced up to as significant extent, i.e. from 15.91% to .95% without using any physical filter.

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