

Analysis of Six Pulse Modulation High Frequency Three Phase Inverter

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Abstract-Fuel cells have achieved global attention as alternative power sources due to the environmental concerns. The prime focus of this paper is to design a three phase inverter fed with hybrid modulation technique suitable for fuel cell applications. Hybrid modulation technique comprises two different modulation schemes. Unlike conventional sinusoidal pulse width modulated inverter this inverter needs only one third modulation of switching devices reducing the switching losses. It reduces the control complexity owing to single-reference three-phase modulation as compared to conventional three-reference three-phase SPWM. In addition, it relieves the necessity of dc-link capacitor reducing the cost and volume. Eliminating dc link capacitor helps in retaining the modulated information at the input of the three-phase inverter. At any instant of line cycle, only two switches are required to switch at HF and remaining switches retain their unique state of either ON or OFF. At the same time inverter devices are not commutated when the current through them is at its peak value. Drop in switching loss is very high in comparison with a standard voltage source inverter (VSI) employing standard three-phase sine pulse width modulation. This proposed work explains operation and analysis of the HF two-stage inverter modulated by the proposed modulation scheme. MATLAB 7.1 software is used for the analysis of the system.

Index Terms: Electric vehicles, fuel cell vehicles, high-frequency, six-pulse modulation, three-phase inverter

I. INTRODUCTION

In the future, many local energy sources, such as photovoltaic units, fuel cells, small turbines, small hydro electric plants, and other dispersed sources will become a larger fraction of our electrical supply. A fuel cell uses the chemical energy of hydrogen to cleanly and efficiently produce electricity, with water and heat as byproducts. Fuel cells are unique in terms of variety of their potential applications; they can provide energy for systems as large as a utility power station and as small as

a laptop computer. Fuel cells have several benefits over conventional combustion based technologies currently used in many power plants and passenger vehicles. Output of fuel cell is a variable dc hence a converter is needed to regulate the fuel cell output voltage and power flow. Both permanent magnet and induction motor machines for fuel cell generation require high voltage at high speed and high power. Thus to achieve high speed and high power, the inverter and the motor must be oversized if only a traditional pulse width modulated (PWM) inverter is used as a power converter. In addition the fuel cell has a relatively slow response and unidirectional power flow. Therefore an energy storage device is always needed to handle load dynamics and regenerative braking. The present prototype has no energy storage device, battery or ultra capacitor and thus cannot handle load dynamics and regeneration. Frequent startup of the fuel cell presents a huge challenge at low voltage, high current for successful continuous generation of electricity. This is almost impossible for the traditional PWM inverter. The voltage boost function is particularly preferable during freeze start. Providing a large amount of boost was prohibitive due to the large device stresses and parasitic circuit elements. Therefore boot topology utilizing high frequency transformer was considered.

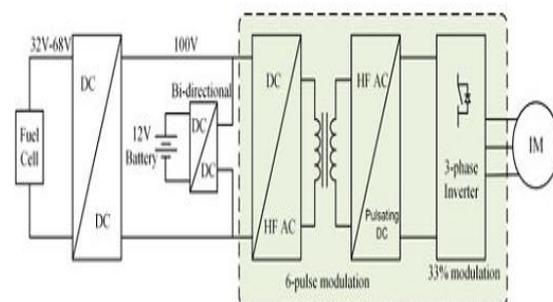


Fig. 1. Functional diagram of a fuel cell propulsion system.

A single reference signal is used for SRSPM implementation. Second modulation is 33% (or one third) modulation adopted for a three-phase inverter that generates balanced three-phase voltage [1]. In 33% modulation, only one leg is modulated at a

time. It reduces the average switching frequency and limits the switching losses to 33% of the conventional value. Cascading does not affect the modulation implementation, or in other words the proposed SRSPM is applicable to single full-bridge unit too. Interleaving is shown to increase power transfer capacity [5]. Fig.1. Functional diagram of a fuel cell drive system. Though a similar hybrid modulation technique for inverter control has been proposed earlier models, the front-end dc/dc converter essentially has minimum three full bridges employing standard three-phase SPWM with three references [9][10][13]. It results in complex control and has major issue of circulating current among the bridges conducted by semiconductor devices. If one bridge fails, the modulation fails, i.e., the However, the proposed modulation scheme works with single bridge too owing to single reference approach. Devices at symmetrical location in two bridges are operated by identical gating signals. The merit of this innovation is unique single reference that is developed to contain information of six-pulse waveform. Since, identical single reference is given to both the front-end bridges, in case of failure of one of the bridges; the other bridge still produces the same six-pulse pulsating waveform at the dc link and then the balanced three-phase inverter output voltage.

Therefore, single-reference modulation with interleaved or cascaded front-end offers higher reliability as compared to that proposed previously. This technique is used in the different applications like Fuel cell vehicles, Electrical vehicles, Uninterrupted power supply (UPS), PV Systems, Islanded microgrid, Solid state transformers. The circulating current between the bridges is eliminated. Conventional modulation [9], [10] suffers from circulating current between the bridges (i.e., through semiconductor devices) causing additional losses. This paper objective is to explain steady-state operation and analysis of the two stage HF inverter employing the proposed modulation scheme, reported in Section 2. The design of the converter has been illustrated in Section 3. The design and analysis have been verified by simulation results using MATLAB 7.12.0.635 in Section modulation scheme. Pulsating dc voltage does not contain six-pulse information anymore, and hence, the inverter is not able to produce balanced three-phase output. The proposed modulation has unique single

reference signal. Even if a bridge fails, the other will maintain six-pulse information in pulsating dc-link voltage and inverter is still able to produce balanced three-phase voltage. It is, therefore, robust and offers higher reliability.

The overall system has the following merits:

- 1) Elimination of dc-link electrolytic capacitor: reduces volume of system and improves reliability
- 2) Reduced average switching frequency of inverter: at any instant of time, only one leg of inverter is modulated at HF keeping other two legs at same switching state. This reduces the switching losses and improves efficiency. Switching losses are further reduced because the devices are not commutated when current is at its peak.
- 3) Single reference front-end modulation: A single reference signal is used to implement six-pulse modulation to produce pulsating dc voltage at the dc link. The proposed inverter has better reliability compared to existing topologies owing to single-reference modulation.

II. RELATED WORK

Previously [9] and [10] having three full-bridges at front-end are used and standard three-phase SPWM is employed that uses three single phase sine references. Three single-phase HF transformers are connected to compute maximum line-to-line and generate pulsating dc voltage with six-pulse information. Modulations of three full-bridges are dependent mutually on each other to produce pulsating six-pulse waveform at the dc link of the inverter.

In this case, accurate functioning of each front-end full bridge is necessary to maintain six-pulse waveform information at the dc link and later to obtain balanced three-phase inverter output voltage. From the reliability point of view, failure of a full-bridge results in failure of the system. This is a major weakness of the three-reference modulation [9][10]. This paper proposes a single-reference modulation to do the same task, i.e., producing pulsating six-pulse waveform at the dc link and

producing balanced three-phase sine output. Interleaving (two bridges at front-end) is done to increase the power transferring capacity [1].

III. OPERATION AND ANALYSYS OF THE CONVERTER

In this section explained the steady state operation and analysis of the modulation technique. Two full-bridge converters are cascaded or interleaved at front-end in parallel input series output to increase the power transfer capacity as shown in Fig.2. Both full-bridges are modulated using identical six-pulse modulation producing HF pulsating dc voltage V_{dc} , which is given to a standard three-phase inverter. Modulation of the two stages is planned, developed, and implemented, so as to reduce the switching losses of inverter while making dc link capacitorless. The three-phase inverter is modulated to shape this HF pulsating dc-link voltage to obtain balanced three-phase sine inverter output voltages of required frequency and amplitude after filtering.

The following assumptions are made for easy understanding of the analysis of the converter:

- 1) All semiconductor devices and components are deal and lossless.
- 2) Leakage inductances of the transformers have been neglected.
- 3) Dc/dc converter cells are switched at higher frequency compared to the inverter.

Therefore, current drawn by the inverter, i_{dc} remains approximately constant over one HF switching cycle of the dc/dc converter. Magnetizing inductances of the HF transformers are denoted as L_{ma} and L_{mb} in Fig.2. one third of the line cycle. An important note is the devices do not commute when current through them is at its maximum value

A) Modulation:

The switch pairs $M1a-M2a$ and $M3a-M4a$ are operated with complementary signals. Reference signal V_{ref} is a six-pulse waveform that is obtained from the rectified output of three-phase line-line voltage as shown in Fig.2. As the name suggests, the reference voltage is having frequency of $6 \times$ ac line frequency. These six equal pulses are flagged as T1 to T6. During each of these pulses, only one leg of the inverter is modulated at HF whereas remaining two legs are steady at their switching state.

The modulating sequences of the inverter switches S1-S6 are given in Table 1, which are compared with carrier waveform to get gating pulses for the devices. During time interval T1, S4 and S5 are ON, and S3 and S6 are OFF. S1 and S2 are modulated at HF by using V_{ab}/V_{cb} as modulating signal. It can be clearly observed from Fig.3 that only two (1 leg) of six devices (3 legs) are switched at HF resulting in reduction of number of switching instants in a line cycle. Similar procedure is followed for remaining five segments. In a complete line cycle, each semiconductor device is switched at HF only for This modulation technique is very easy to implement by using three-phase line-line voltages as This further reduces the switching losses lower than 33%. The modulation given in Table 1 produces a low harmonic distortion of the output waveforms as compared to previous method that gives an unsymmetrical wave shape. In the proposed method, exact modulating signals are calculated by considering variation in average dc-link voltage in six-pulse form references shown in Fig.3.

B) Steady State Operation:

The converter operation during different intervals of a HF switching cycle is highlighted by waveforms shown in Fig.4 Gating signals of dc/dc full-bridge converters are shown, where each switch is operated at 50% duty ratio and complementary to other switch in the same leg.

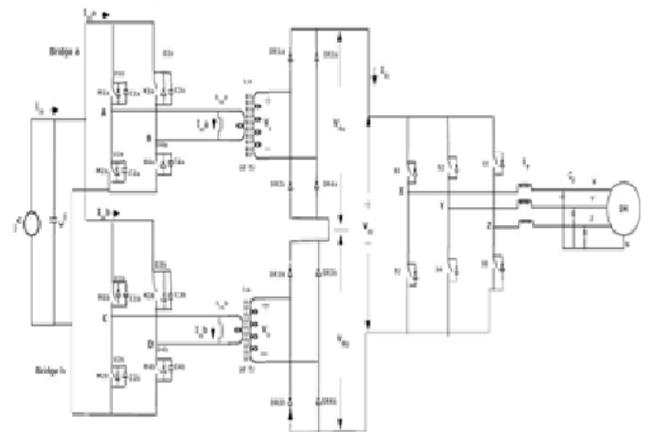


Fig.2. Schematic of the proposed fuel cell inverter system

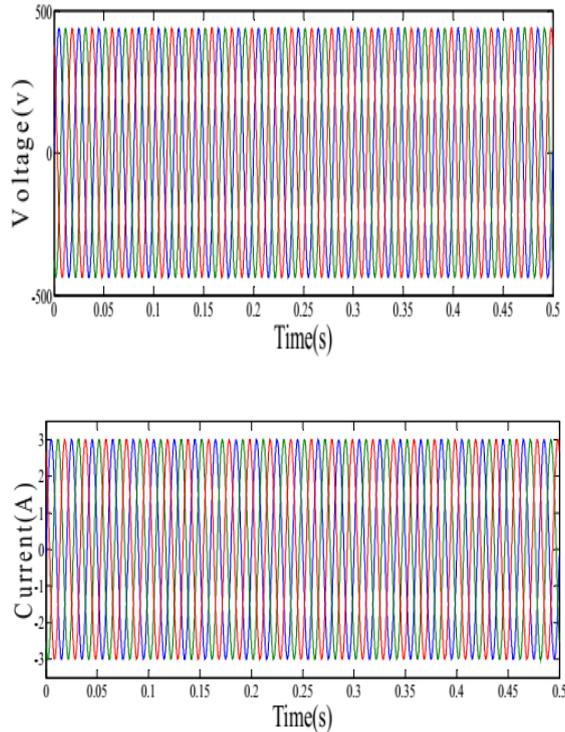


Fig. 3. Simulation results showing output voltages and currents for 0.5kw RL load using fuel cell inverter

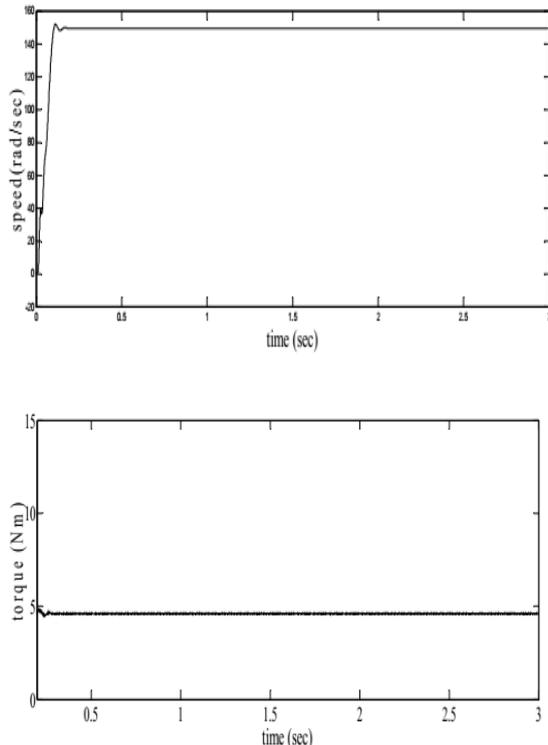


Fig.4. Simulation results showing speed and torque 0.8kw induction motor load using fuel cell inverter

Whenever the diagonal switch pairs are conducting, say M1a and M4a, input voltage V_{in} appears across

the transformer primary and nV_{in} is reflected on the secondary side. On the other hand, when other diagonal pair M2a and M3a are conducting, $-nV_{in}$ is obtained across secondary terminals, where n is the turns ratio of the transformer. Another full-bridge unit is also operated in similar manner applying similar gating pulses to symmetrical devices. Bipolar pulsating voltage is converted to unipolar using full-bridge diode rectifier circuit. Rectifier outputs from two cells are connected in series to add the voltage level. The average value of the rectifier output voltage at dc link over a switching cycle is obtained as

$$V_{Ra} = V_{Rb} = 2D \cdot n \cdot V_{in} \dots\dots\dots(1)$$

$$V_{dc} = V_{Ra} + V_{Rb} = 4D \cdot n \cdot V_{in} \dots\dots\dots(2)$$

Where D is the duty ratio of the converter. In the proposed modulation scheme, the duty ratio D is generated from V_{ref} which is a six-pulse waveform. The duty ratio varies between its maximum D_{max} and minimum values D_{min} for required three-phase output voltages as the V_{ref} varies at 300 Hz. The maximum value of voltage obtained at V_{dc} corresponds to the peak of line to line inverter output voltage is obtained at D_{max} and is obtained as

$$V_{XY,peak} = 4D_{max} \cdot n \cdot V_{in} \dots\dots\dots(3)$$

Where $V_{XY,peak}$ is the peak of line-line output voltage. Magnitude of output voltage can be varied by varying the reference voltage V_{ref} , which changes the range of operating duty ratio D_{min} and D_{max} .

C) Switching Losses:

As discussed and explained previously, it is clear that devices of the three-phase inverter switch at HF only for 1/3rd of the line cycle. The switch is kept in the on-state for 1/3rd of the cycle conducting the peak current of the output line current when the output power factor is unity and in the OFF state for rest 1/3rd of the line cycle. Similarly, line current is at its negative peak during off-state of the top switch and on-state of the bottom switch. Devices are switching at HF when the line current crosses zero. The switching loss in the inverter devices reduces by

around 7.5 times for the proposed modulation method as compared to the standard sine pulse width modulation (SPWM).

III. INVERTER DESIGNING

The design procedure is illustrated by a design example for the following specifications: Input voltage $V_{in} = 100$ V, output phase voltage $V_O = 110$ V at $f_O = 50$ Hz, rated power $P_O = 400$ W, switching frequency of dc/dc converter $f_{SC} = 100$ kHz, and of inverter $f_{SI} = 40$ kHz.

- 1) Average input current is $I_{in} = P_O / (\eta V_{in})$. Assuming an efficiency η of nearly 95%, $I_{in} = 4.21$ A. Each full-bridge is sharing half of the load, $I_{ina} = I_{inb} = I_{in} / 2 = 2.1$ A.
- 2) Maximum value of average voltage at dc link should be above peak value of line-line output voltage $V_{dc} = \sqrt{3} \cdot \sqrt{2} \cdot V_O = 270$ V
- 3) The turns ratio of the transformers are designed by considering the operating duty ratio of the full-bridge converter as 0.4–0.425.
- 4) The turns ratio of 1.6 is selected allowing safe margin in case of decrease in input voltage below 100V. Transformer primary needs to carry current of $I_{in} / 2 = 2.1$ A.

Rating of the full-bridge converter: Switches M1a–M4a and M1b–M4b are rated to conduct current of $I_{ina} = I_{inb} = 2.1$ A and rated to withstand voltage of $V_{in} = 100$ V.

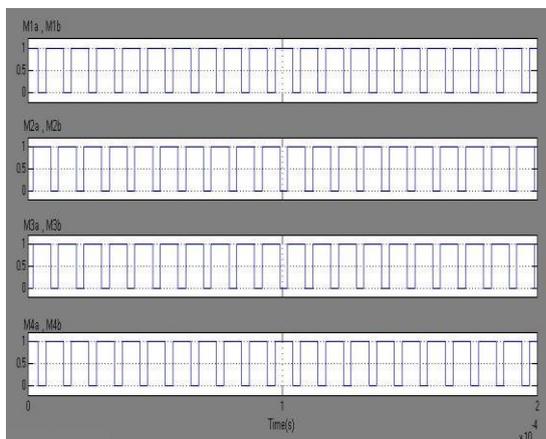


Fig.5. Waveforms showing gating signals of the full-

bridge converter.

IV. SIMULATION RESULTS

The given modulation scheme has been simulated using software package MATLAB 7.12.0.635 for the given specifications. Simulation results are illustrated in Figs. 7 to 8 matching closely with the theoretical predicted waveforms and results. The modulation for the inverter devices is derived by comparing modA, modB, and modC waveforms with the carrier signal of 40 kHz.

Fig.7. Simulation results showing references (V_{ab} , V_{bc} , and V_{ca}), output phase voltages (V_{xn} , V_{yn} , and V_{zn}) and output line current (I_x , I_y , and I_z) waveforms at rated load under the normal operating condition.

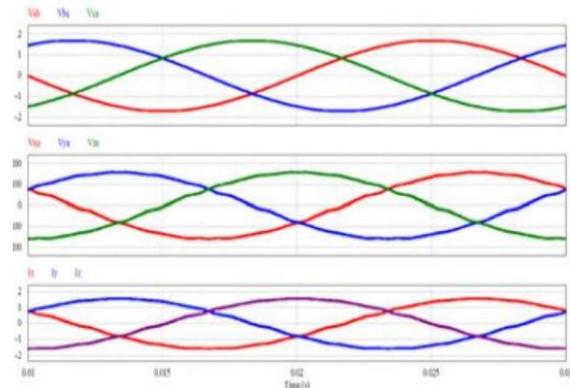


Fig.7 shows three-phase reference voltages used to implement the proposed modulation scheme. Fig.7 also presents the balanced three-phase output voltages of 110 V rms that are obtained across the load and the load currents. The LC filter has eliminated HF components resulting in low harmonic contents (distortion) of the inverter output waveforms.

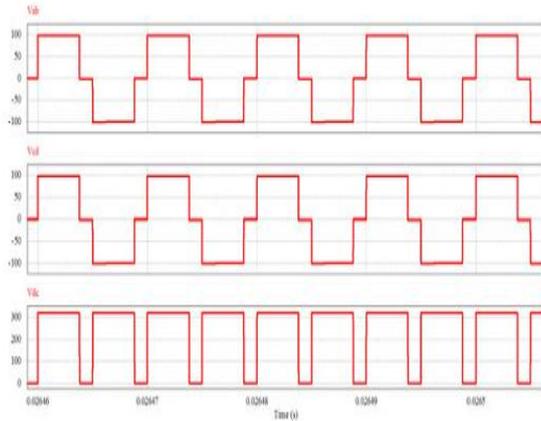


Fig. 8. Simulation output showing voltages VA B , VC D , and Vdc at rated load under the normal operating condition.

The series connected rectifier output voltage is shown in Fig. 8 as explained in the analysis.

V. CONCLUSION

Fuel cells are becoming lucrative solution toward sustainable low carbon cleanmobility owing to zero emission .This paper proposes a novel modulation techniquenamed SRSPM to control front-end full-bridge converter to generate HF unipolar pulsating voltage waveform at dc link having six-pulse information if averaged at HFcycle over line frequency.. Six-pulse is meant for six-pulse waveform that results after rectification of three-phase balanced ac waveforms at 6×of line frequency. It permits the next three-phase inverter devices toswitch at HF during 33.33% (1/3 rd) of the line cycle and remains to stay at steady switching state of ON for 33.33% and OFF for rest 33.33% of line cycle. It results in low average switching frequency or 66.66% reduction inswitching transition losses and improved efficiency.Compared to three-phase inverter, reduction in switching loss up to 86.6% is accomplished. It is suitable for highpower applications like FCVs and EVs, three-phase uninterruptible power supply (UPS), islanded or standalone micro-grid, and solid-state transformer.

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