

High Frequency and Multi Level Inverter using HM Technique for Fuel Cell Drives

Abhinav¹, J Ranga²

^{1,2} EEE Department, SreeDattha Institute of Engineering & Science

ABSTRACT-- A hybrid modulation technique consisting of single-reference six pulse modulation (SRSPM) for front end dc/dc converter and 33% modulation to the three-phase inverter. Applying proposed SRSPM to control front-end dc/dc converter, high frequency (HF) pulsating dc voltage waveform is produced, that is equivalent to six-pulse output at $6 \times$ line frequency (rectified 6-pulse output of balanced three-phase ac waveforms) once averaged. It reduces the control complexity owing to single-reference three-phase modulation as compared to conventional three-reference three-phase SPWM. Also it eliminates the necessity of dc-link capacitor which reduces the cost and volume. Eliminating dc link capacitor helps in retaining the modulated information at the input of the three-phase inverter. It requires only 33% (one third) modulation of the inverter devices to produce balanced three-phase voltage waveforms resulting in significant saving in (at least 66%) switching losses of inverter semiconductor devices. 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 sinusoidal pulse width modulation. This proposed work explains operation and analysis of the HF two-stage inverter modulated by the proposed modulation scheme. MATLAB 7.12.0.635 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

Fossil fuel resources are limited and vanishing at an alarming rate, the global demand for oil and coal has increased significantly in recent years. To produce the green and efficient energy research is going on. The steady-state operation and analysis of the two stage HF inverter controlled by the proposed modulation scheme have been discussed. Simulation results are verified by using MATLAB 7.12.0.635 to the proposed analysis. This hybrid modulation technique also uses for high power applications like FCVs and EVs, three-phase uninterruptible power supply (UPS), islanded or standalone micro grid, and solid-state transformer. Nowadays the technology is improved very much in that part of technology to develop the fuel cells. These fuel cells are producing the electrical energy through the chemical reaction of the hydrogen and oxygen. But here fuel cell stack gives the very small amount of dc voltage (32V-68V). We have to use this energy and convert into large scale voltage. In the part of energy conversion here proposes a new conversion technique.

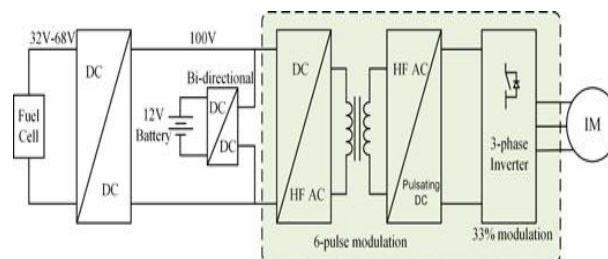


Fig.1. Functional diagram of a fuel cell drive system

The single-stage inverter is the very easiest topology with least component number and high efficiency. But low voltage fuel cell stack needs a multilevel inverter to boost its low voltage to generate three-phase voltage signals. HF modulation is adopted to achieve compact, low cost, and light weight system. Therefore, two stage HF inverter consisting of front-end dc/dc converter followed by a standard three-phase pulse-width modulated (PWM) inverter as shown in Fig.1 is an alternative solution. This paper proposes a hybrid modulation technique that comprises two different modulations for the two stages. Single Reference Six Pulse Modulation (SRSPM) is converter to produce HF pulsating dc voltage having six pulse information on an average. 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. 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. 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 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. Previously and 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.

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]. 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 suffers from circulating current between the bridges (i.e., through semiconductor devices) causing additional losses.

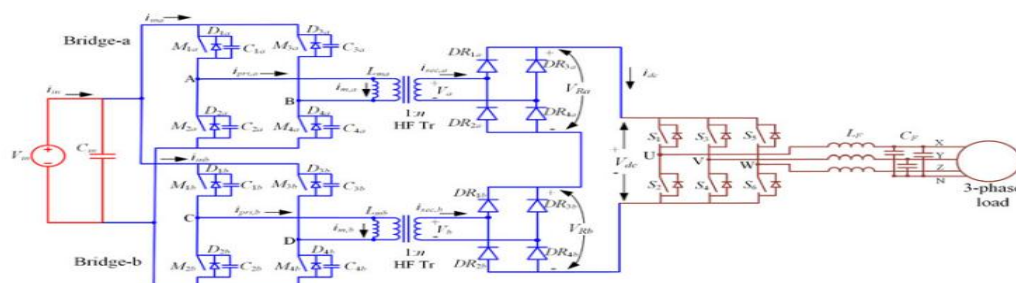


Fig.2. Schematic of the proposed fuel cell inverter system

II OPERATION AND ANALYSIS 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 capacitor less. 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 ideal 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 commutate when current through them is at its maximum value.

TABLE I
MODULATION SIGNALS FOR SWITCHING OF THE INVERTER

	T_1	T_2	T_3	T_4	T_5	T_6
S_1, \bar{S}_2	V_{ab}/V_{cb}	1	1	V_{ac}/V_{bc}	0	0
S_3, \bar{S}_4	0	0	V_{bc}/V_{ac}	1	1	V_{ba}/V_{ca}
S_5, \bar{S}_6	1	V_{cb}/V_{ab}	0	0	V_{ca}/V_{ba}	1

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. The duty ratio of front end converter varies nearly 15% over frequency of $6 \times$ line frequency. Fig. shows three-phase reference voltages used to implement the proposed modulation scheme. In the proposed inverter system it have two full bridges at front-end. If both the bridges are working properly it obtains the outputs shown in Fig. It contains the balanced three-phase output voltages of 110 Vrms that are obtained across the load and the load currents. 2) Maximum value of average voltage at dc link should be above peak value of line-line output voltage $V_{dc} = \sqrt{3} \cdot 2 \cdot V_O = 270$ 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. From (2), value of turn's ratio n is

$$n = \frac{V_{dc}}{4 \cdot D \cdot V_{in}}$$

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. 4) 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. and current of I_{dc} given by

$$I_{dc} = \frac{P_O}{V_{dc, min}}$$

Where $I_{dc} \approx 1.71$ A. Voltage rating of rectifier diodes, $VDR = nV_{in} = 200$ V.

6) Inverter circuit: Voltage across inverter switches is selected based on the maximum voltage across dc link, which is equal to $2n \times V_{in}$. The RMS current rating of the switches is the same as the output current I_O . For the given specification, voltage rating is equal to 400V and current rating is 1.71 A.

7) Filter design: Filter inductance is calculated such that the voltage drop across the inductor is less than 2% of the nominal voltage during the full-load condition.

$$L_F = \frac{V_O \cdot 0.02}{2\pi \cdot f_O \cdot I_O}$$

where I_O is the output current. For the given specifications, L_F is obtained as 10 mH. Filter capacitance is calculated from the cut-off frequency of the low-pass filter. For this application, one tenth of the inverter switching frequency f_{SI} is selected as the cut-off frequency. Filter capacitor is calculated as

$$C_F = \frac{1}{4\pi^2 \cdot f_c^2 \cdot L_F}$$

where f_c is the cut-off frequency of the filter. For $f_c = 4$ kHz, the capacitor C_F is obtained as $0.16 \mu\text{F}$. Given modulation scheme has been simulated using software package MATLAB 7.12.0.635 f

IV. SIMULATION RESULTS

The given specifications. Simulation results are illustrated in Figures. matching closely with the theoretical predicted waveforms and results. The modulation of the inverter devices is derived by comparing modA , modB , and modC waveforms with the carrier signal of 40 kHz. Switches are commutated at HF for only one third of the line cycle i.e., $V_{CD} = 0$ and, therefore, only “bridge-a” is resulting in significant saving in switching losses. It is also observed that only one of the legs is switching at HF, remaining two device legs being connected to either V_{dc} (off) or 0 (on). In order to generate pulsating dc voltage at V_{dc} , semiconductor devices are modulated with the varying duty ratio generated from the six-pulse signal, V_{ref} shown in Figure. The duty ratio of front end converter varies nearly 15% over frequency of $6 \times$ line frequency. Fig. shows three-phase reference voltages used to implement the proposed modulation scheme. In the proposed inverter system it have two full bridges at front-end. If both the bridges are working properly it obtains the outputs shown in Fig. It contains the balanced three-phase output voltages of 110 Vrms 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.

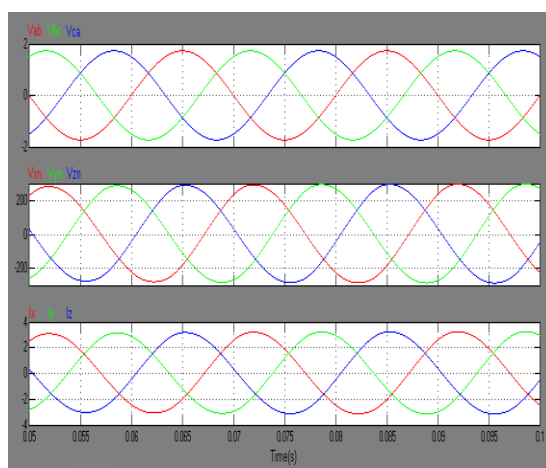


Fig3 Three-phase output voltages

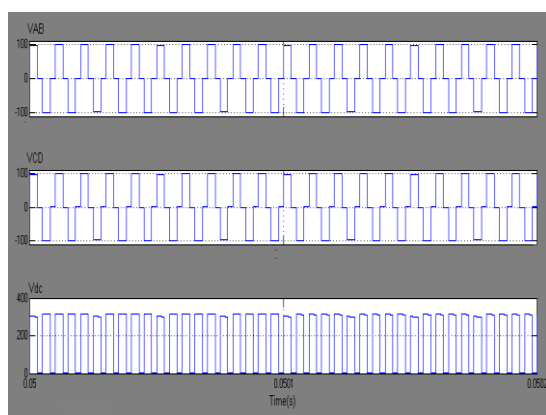


Fig4 Gate voltage of switch S1VGS,1(top, scale: 10 V/div) and voltage across it VDS,1

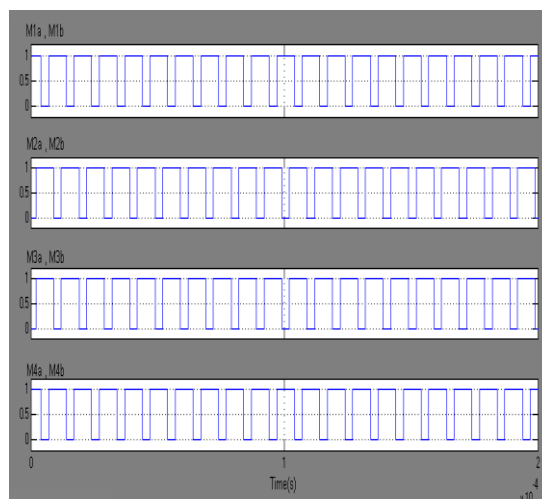


Fig5 Gate signals to inverter top switches demonstrating 33% modulation

IV. CONCLUSION

Volume, cost, efficiency, reliability, and robustness are the important attributes of the power electronics system to be addressed. This modulation technique named 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 HF cycle over line frequency. The proposed modulation technique eliminates the need for dc link capacitor and feeds directly HF pulsating dc voltage to a three-phase inverter. This pulsating waveform is utilized to generate three-phase output voltage at reduced average switching frequency (one third of the inverter switching frequency) or 33% commutations of inverter devices in a line cycle. The steady-state operation and analysis of the two stage HF inverter controlled by the proposed modulation scheme have been discussed. Simulation results are verified by using MATLAB 7.12.0.635 to the proposed analysis. This hybrid modulation technique is also uses for high power applications like FCVs and EVs, three-phase uninterruptible power supply (UPS), islanded or standalone microgrid, and solid-state transformer.

REFERENCES

- [1] Udipi R. Prasanna and Akshay K. Rathore, "A Novel Single-Reference Six-Pulse-Modulation (SRSPM) Technique-Based Interleaved High-Frequency Three-Phase Inverter for Fuel Cell Vehicles" in *Proc. IEEE Trans. On Power Electron.*, vol. 28, no. 12, pp.5547-5556, Dec.2013.
- [2] A. Emadi and S. S. Williamson, "Fuel cell vehicles: Opportunities and challenges," in *Proc. IEEE Power Energy Society General Meeting*, 2004, pp. 1640–1645.
- [3] S. Aso, M. Kizaki, and Y. Nonobe, "Development of hybrid fuel cell vehicles in Toyota," in *Proc. IEEE Power Convers. Conf.*, 2007, pp. 1606–1611.
- [4] A. Emadi, K. Rajashekar, S. S. Williamson, and S. M. Lukic, "Topological overview of hybrid electric and fuel cell vehicular power system architectures and configurations," *IEEE Trans. Veh. Technol.*, vol. 54, no. 3, pp. 763–770, May 2005.
- [5] A. Khaligh and Z. Li, "Battery, ultracapacitor, fuel cell, and hybrid energy storage systems for electric, hybrid electric, fuel cell, and plug-in hybrid electric vehicles: State of the art," *IEEE Trans. Veh. Technol.*, vol. 59, no. 6, pp. 2806–2814, Jul. 2010.
- [6] J. M. Miller, "Power electronics in hybrid electric vehicle applications," in *Proc. 18th IEEE Appl. Power Electron. Conf.*, Miami Beach, FL, USA, Feb. 2003, vol. 1, pp. 23–29.
- [7] A. Averberg, K. R. Meyer, and A. Mertens, "Current-fed full-bridge converter for fuel cell systems," in *Proc. IEEE Power Energy Society General Meeting*, 2008, pp. 866–872.
- [8] S. S. Williamson and A. Emadi, "Comparative assessment of hybrid electric and fuel cell vehicles based on comprehensive well-to-wheels efficiency analysis," *IEEE Trans. Veh. Technol.*, vol. 54, no. 3, pp. 856–862, May 2005.