AC Link Inverter Based on Multiple Carrier PWM For Fuel Cell

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Abstract—The paper suggests the development of a low cost fuel cell inverter system. The approach consists of a three-terminal push-pull inverter to boost the fuel cell voltage of 24V to ±220V ac with HF transformer (1KHz frequency). High-frequency ac link conversion offers a possible way to reduce the number of power stages, in the form of a cycloconverter. The approach keeps the number of stages and magnetic elements low while providing galvanic isolation. Either SCRs or IGBTs can be used as output devices, which provide an unusual cost/performance trade-off possibility. Gate drives and other control elements are also simplified. The design provides excellent performance with a minimum filter components and a simple control.

Keywords—Cycloconverter, Inverter, Simulation, Multivibrator, Fuelcell

I. INTRODUCTION

For the power conversion system where linkage with ac system line is required, the HF (high-frequency) link converter topology has been attracting special interests recently, because it enables the power converters to be compact and light-weight. Two types are considered in the high frequency converters. One is a dc/dc converter type and other is a cycloconverter (ac/ac) type.

This paper details the application of low cost fuel cell inverter using multiple carrier PWM for ac-ac converter. The power conversion is more direct (two stages). Also PWM cycloconverter, with or without natural commutation, and conventional PWM inverter is unified through a multiple carrier PWM framework. Issues about complexities are resolved. Multiple carrier PWM methods lead HF link inverters that are about as simple as conventional PWM inverter.

The visions of a fuel cells potential are diverse. They include fuel cells powering cars, operating as backup or even primary power for your home from a shed-sized fuel-cell system, and providing power for larger commercial buildings and computer installations. Such systems can produce significant power. Though practical model is build but with some minor modifications commercial fuel cell inverter can be built.

II. OVERVIEW OF SCHEME

Fig.1 shows block diagram for the scheme. Input is 24V battery/fuel cell with capacitor for filter. Inverter is of push pull configuration with 1 KHz frequency. Cycloconverter is having 50Hz frequency. Isolation is obtained from high frequency transformer.

i. Control Block for Inverter

Gate pulses are applied to switches of push pull inverter. Phase delay is introduced between pulses as shown in Fig 2. Gate pulses are in synchronization with 2 KHz ramp.

ii. Control Block for Cycloconverter

For control block Multiple Carrier PWM scheme is used. In this high frequency carrier is used along with modulating signal. Carrier could be triangle or ramp. Modulating signal is low frequency component. For multi carrier operation instead of two carriers two modulating signals are taken which solve the purpose and is valid for single phase cycloconverter. Carrier is 2 KHz ramp and modulating signal is 50Hz sine wave. Control is applied to cycloconverter side while inverter gate pulses are synchronized with ramp at 1KHz.
As shown in Fig. 3 control module contains ramp generator of frequency 2 KHz which also gives square wave of 1 KHz to be applied as control for forward converter i.e. inverter.

Sine wave obtained at 50 Hz is modulating signal. For multiple carrier operation this sinusoidal waveform is phase shifted by 180°.

By comparing carrier and modulating signal PWM output is obtained. This PWM output is advanced or delayed for achieving phase advanced and phase delayed trigger pulses respectively. Such pulse train is obtained using multivibrator (delay block in Fig. 3).

The delayed waveform is blanked when the current is negative, while the advanced waveform is blanked when the current is positive.

The two multivibrators are triggered from the rising edge of the respective comparator to produce a 15 μs gate pulse train. The upper multivibrator creates a phase-delayed gate pulse train to be used when load current is positive, while the lower multivibrator creates a phase-advanced gate pulse train to be used when the load current is negative. Simple logic is used with a current comparator to separate the positive and negative current conditions.

These trigger pulses are combined with another input obtained from current polarity detector. This current polarity detector detects current direction across load.

Thus trigger pulses obtained are applied to positive and negative converter of cycloconverter through driver.

### iii. Power Block

Power block is described under two sections, as this consists of primary side and secondary side with isolation as shown in Fig. 3.

The primary side, inverter operation is obtained through push-pull configuration while output is single phase bridge consisting of 8 SCRs connected in antiparallel. RC snubber is designed for switches.

### iv. Inverter

As shown in Fig. 4, inverter consists of push pull inverter which converts 24V dc to 96Vp-p, 1 KHz square wave. This push pull inverter uses two MOSFETs as switches. Driver for MOSFET is obtained by transistorized circuit. Driver signals are synchronized with 2 KHz ramp. Inverter switches at 1 KHz. Filtering of dc voltage from battery is done through capacitor.

### v. Cycloconverter

Fig. 5 shows schematic for ac-ac converter along with current polarity detection. Commutation of cycloconverter during the zero crossing of load current is an important control issue, well understood from conventional ac cycloconverter results. Ideally, the current polarity detection scheme in Fig. 5 would use the “fundamental current zero”. While this scheme results in ideal commutation with no cross-over distortion, it is known to be difficult to implement in practice. Instead, Fig. 5 uses a modification to the “first current zero”
As shown in block diagram secondary of power module consists of single phase ac-ac converter with 8 SCRs along with 4 RC snubbers. Load connected is RL and switching is controlled from trigger pulses obtained from control module whose feedback is from current polarity detector, which senses the load fed from cycloconverter. Isolation between source and load is obtained using HF transformer. This transformer uses ferrite core to achieve high frequency square wave transfer.

III. DESIGN OF INVERTER CONTROL BLOCK

Synchronized square pulse is obtained which is phase shifted and delayed before applying to switches.

i. Design of Synchronized Square Pulse

Synchronized square pulse is achieved from ramp generator as shown in Fig.6. D flip flop IC4013 is used with reset on ON facility. Clock is given through non-inverting buffer consisting of CE amplifier with BC 546. Diode IN4148 is used as edge detector and for bypassing negative cycle.

IC4013 is used to generate square wave of 1 KHz synchronized with 2 KHz ramp. Clock frequency is also 2 KHz. The CD4013B dual D-type flip-flop is used.

ii. Design of Gate Pulse

The 50% duty cycle for gate pulses still support pulse transformer coupling, retaining the simplicity of the gate drive isolation. The PWM cycloconverter process scales directly to higher switching speeds possible with these devices. NAND gate IC 4093 is used for inversion in gate pulse. Delay is obtained using standard RC circuit.

R = 10 KΩ
C = 0.01 μF
R*C = 0.1ms

\[ fo = \frac{R2}{R3} \times \frac{Vp-p}{2*Vsat} \]
Let \( Vp-p = 7V \)
R2 = 10 KHz
Vsat = 12V
R3 = 34.28 KΩ
Choose R3 = 22K+10Kpot
\[ fo = \frac{R3}{4} \times R1*C1*R2 \]
\[ R1*C1 = 0.4ms \]
Let C1 = 0.47μF
R1 = 851 Ω
Let R1 = 1KΩ

Where \( fo \) --------Output frequency in Hz.
Vp-p-------- peak to peak output voltage

As shown in fig 6, buffering and amplification is obtained from 3A op-amp. 47 KΩ for high input impedance and combination of 6 KΩ and 1 KΩ resistance for dc level shift hence obtaining swing of ramp across zero. Final value adjusted to 3 Vp-p and 2.5 KHz frequency. Quad op-amp IC348 is used in circuit. LM348 is chosen for ramp generation.
a. Design of Sine Wave Generator

Sine wave is obtained using bridge oscillator [13] as shown in Fig.9. Designing is done at 12Vp-p, 50 Hz frequency. 
\[ f_0 = \frac{0.159}{R_C} \]
\[ R_C = 3.18 \text{ms} \]
Let \( C = 0.47 \mu\text{F} \)
\( R = 6.7 \text{K}\Omega \)
Gain \( R_0 = 2 \)
Let \( R_1 = 5.1 \text{K}\Omega \)
\( R_f = 10 \text{K}\Omega \)
\( 2V_{p-p} \) is achieved using potential divider as shown in Fig. 9. Buffer is also connected. This sine wave is further inverted using op-amp as inverting amplifier. Gain for this op-amp is set as 1 with combination of 10 K and 9.1 K and 2K pot.

b. Design of Comparator

For obtaining PWM comparison is done between ramp and sine using high speed voltage comparator dual comparator LM319. Modulation index is set to 0.66.

c. Design of Multivibrator

The MC14538B is a dual, retriggerable, resettable monostable multivibrator. It may be triggered from either edge of an input pulse, and produces an accurate output pulse over a wide range of widths, the duration and accuracy.

of which are determined by the external timing components, \( CX \) and \( RX \).
For 15\( \mu \)s delay value of \( CX \) and \( RX \) are chosen as 0.01\( \mu \)F and 1.5K\( \Omega \) respectively.

d. Design of Logical Unit

- Design for Delayed and Advanced circuit- NOR (IC4001) logic is used for obtaining phase advanced and phase delayed trigger pulses.
Design for Feedback Network - Single comparator is required for comparing feedback current obtained from load and PWM output obtained. Input is connected in differential mode as shown in Fig.12.

Both the inputs and the outputs of the LM311 can be isolated from system ground, and the output can drive loads referred to ground, the positive supply or the negative supply.

e. Design of Driver

The driver circuit of cycloconverter consists of Pulse Transformer and transistors along with diode and resistances. As cycloconverter is having SCRs as switches only edges are required for trigger. To obtain voltage level transistor is used as an amplifier. Standard configuration is applied for achieving trigger pulses as shown in Fig.13. Transistor BD139 is used as driver and BC546 as buffer. Such unit is used for each SCR.

IV. POWER CIRCUIT DESIGN

i. Design of Inverter

Inverter is designed using push pull configurations and calculations are done as per requirement. Gate pulse is obtained from circuit shown in previous chapter. MOSFET is chosen for high frequency switching. Two 12V batteries are connected in series for obtaining 24V as fuel cell is not available. Batteries used are of standard company with 1A-Hr rating.

ii. Design of Push Pull Inverter

24 Vdc is converted into square wave of 1 KHz frequency and amplitude of 48V at primary of output transformer using push-pull inverter. This is achieved by circuit shown in Fig.14.

Care is taken that switch has low saturation voltage and breakdown voltage is two to three times the supply voltage. Isolation is obtained through HF transformer which is described in the next section. Capacitor value 220μF/63V is connected across 24V battery for filtering.

Edc = 24V
Eout = 220V
Po = 200W
Io = 1A
Let η = 70%
Pin = 285W
Iin = Pin/Edc
= 6A

IRF540N Power MOSFET is used.

iii. Design of MOSFET Snubber

fs = 1KHz
Edc = 24V
iL = 6A
Let L = 25 μH
tf = 40 x 10^-9 s
where
tf is fall time
fs switching frequency
C = L*tf / Edc
= 6 * tf / 24
C = 0.01μF
L = Edc*tr / iL
tr = 6.25 μs
where tr is rise time
di/dt = iL/tr
= 0.96A/μs

Switch ON
di/dt = 0.24 A/μs
R = √(4*L/C)
R = 100 Ω

Hence values for snubber are chosen as 100 Ω, 1W and 0.01μF/250V.
iv. Design of Transformer

Ferrite core is used for transformer as operation frequency is 1KHz and input is Square Wave. Core is selected as per power requirement.

Edc = 24V  
Eout = 220V  
Po = 200W  
Io = 1A  
Let η = 70%  
Pin = 285W  
Iin = Pin/Edc  
= 6A  

As per calculations core required was EE-65x33x28 but due to its non-availability core used is EE-55x27x21 type 5s  
Area = 20mmx17mm  
N = Eout/Edc  
= 5  

\[ Ns = \frac{Eout \times 10^5}{4 \times B_{max} \times A \times f} \]

Bmax = 4800G  
Br = 1800G  
Hc = 11.9A/m  
Let Bmax = 3150G  
Calculating from above equation  
Ns = 462  
Np = 93  

As push pull type hence each primary winding will have 93 turns each.  
Maximum current rating is reduced due to core used.

v. Design of ac-ac Converter

Secondary of high frequency transformer drives bridge of SCRs connected in anti-parallel and bridge is working as cycloconverter. SCRs are triggered from pulse transformer.

vi. Design of Cycloconverter

As explained in a previous section current is approximately 1A hence SCR rating is chosen accordingly. As shown in Fig.15 eight SCRs are connected in anti-parallel to achieve ac-ac converter configuration. T1-T4 comprise of positive converter while T5-T8 comprise of negative converter.

SCR used is TYN612 having following features:

IT(RMS) -RMS on-state current (180° conduction angle) is 12 A  

VDRM/VRRM Repetitive peak off-state forward voltage is 600 to 1000 V  
IGT Gate Current is 0.2 to 15 mA  

Load is inductive load of 200 mH with self resistance of value 26 Ω.  
Current transformer is connected to obtain current polarity for feedback. Construction of current transformer is done to achieve ratio of 1:300.  
N1I1 = N2I2  
2x1A = 600xI2  
I2 = 3mA  
V = IR  
= 3x10^-3 x 220 Ω,  
= 660mV  

Secondary of current transformer is connected with resistance R(220Ω) whose value is chosen such that voltage obtained across R is enough as input to comparator LM311 connected in triggering circuit for selection of positive and negative converter.

vii. Design of Thyristor Snubber

Let \( \frac{dv}{dt} = 400 \text{ V/μs} \)  
L = 25 μH  
\( \frac{dv}{dt} = E^*R/L \)  
E = 100V  

Where E is secondary voltage peak.  
R = 100 Ω  
R+R1 = 2\sqrt{L/C}  
Let R1 = 0.02 Ω  
C = 0.01 μF
Hence value for snubber chosen is 100Ω, 1W and 0.01μF/250V.

For heat sink PHS-16 is used as power dissipation is very low.

V. SIMULATION & RESULTS

Simulations are done to obtain different gate pulses for different combinations described in table. These gate pulses are combined with square wave as HF link voltage to obtain output voltage. (Refer Table 1)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Carrier Type</th>
<th>Phase Shifter 1</th>
<th>Phase Shifter 2</th>
<th>Phase Shifter 3</th>
<th>Combining Method</th>
<th>Gate Drive Signal Type</th>
<th>Output PWM Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Triangle</td>
<td>0</td>
<td>0</td>
<td>180°</td>
<td>Add</td>
<td>2-Level</td>
<td>Ramp PWM at double fswitch'</td>
</tr>
<tr>
<td>2</td>
<td>Triangle</td>
<td>0</td>
<td>180°</td>
<td>0</td>
<td>Subtract</td>
<td>3-Level</td>
<td>Triangle PWM</td>
</tr>
<tr>
<td>3</td>
<td>Ramp</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Add</td>
<td>2-Level</td>
<td>Triangle PWM</td>
</tr>
<tr>
<td>4</td>
<td>Ramp</td>
<td>180°</td>
<td>0</td>
<td>0</td>
<td>Subtract</td>
<td>3-Level</td>
<td>Ramp PWM at double fswitch'</td>
</tr>
</tbody>
</table>

Fig.16 Simulation Block for scenario 1

Fig.17 Simulation Result for scenario 1

Fig.18 Simulation Block scenario 2
Fig. 19 Simulation Result for scenario 2

Fig. 20 Simulation Block for scenario 3

Fig. 21 Simulation Result for scenario 3

Fig. 22 Simulation Block for scenario 4

Fig. 23 Simulation Result for scenario 4
VI. CONCLUSION

The scheme suggested shows that the number of stages can be reduced, leading to a HF-link conversion approach. The reduction came from recognizing redundancy in the power processing. Without a dc link bus, rectifiers and filter components along with their associated losses are eliminated. Applying the techniques of multiple carrier PWM cycloconversion results are exactly identical to conventional PWM techniques.

The combination of a current-controlled input, adjust the average power demand from a fuel cell, battery buffer, and PWM cycloconverter, provides a reduced parts-count solution compared to conventional boost-forward-inverter cascade topology. The combined converter isolates the fuel cell from its load both electrically and dynamically while reducing parts count and therefore reduces costs.

REFERENCES


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