Florida PEC

UCF

Florida Power Electronics Center

http://FloridaPEC.engr.ucf.edu

Power Electronics for Fuel Cells

Issa Batarseh

Batarseh@mail.ucf.edu

University of Central Florida

Outline

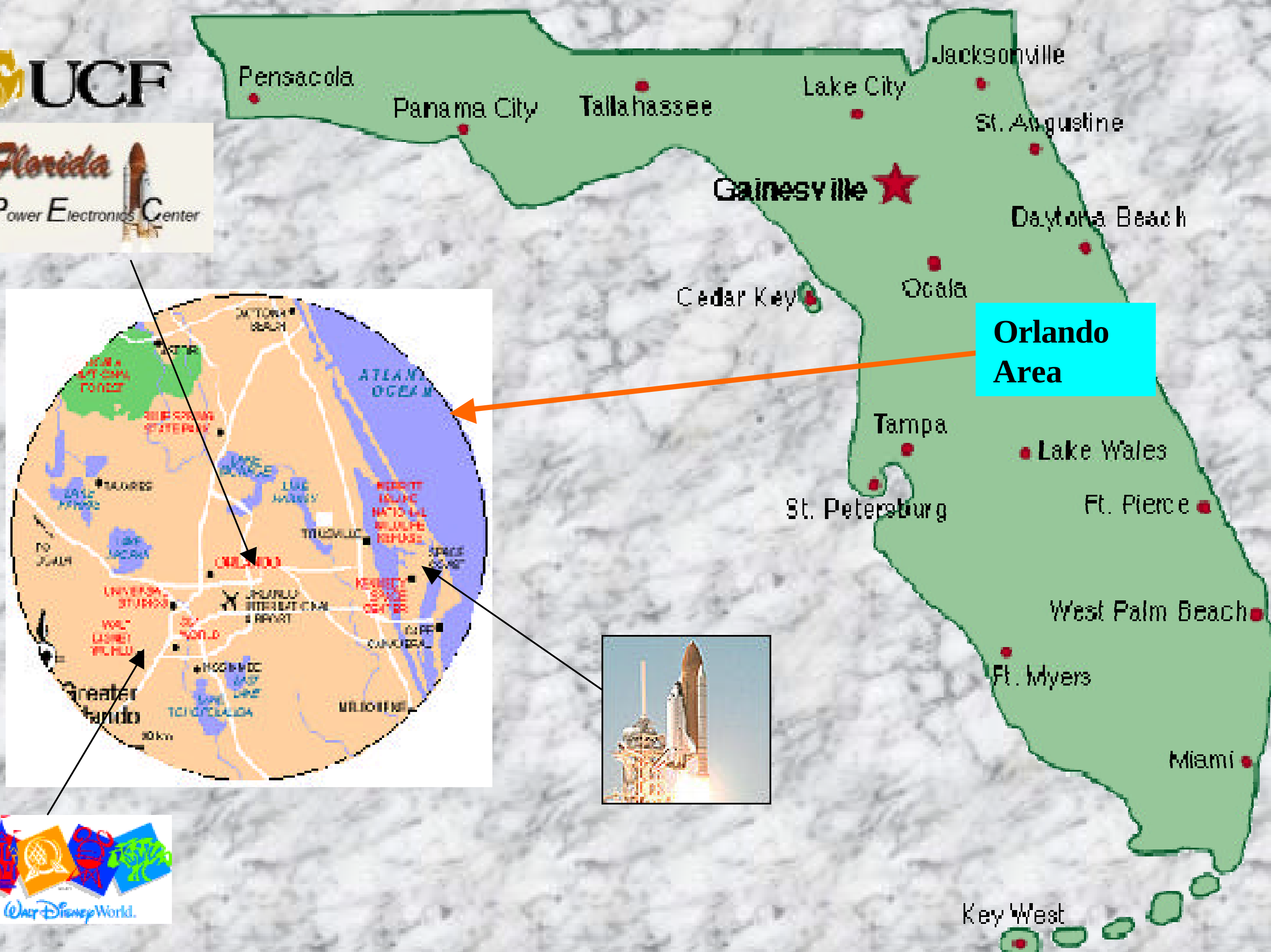
- UCF’s Research Activities
- Fuel Cell Basics
- Fuel Cell Technical Issues
- High Frequency Link Inverter
- Simulation and Experimental Results
- Concluding remarks

WELCOME TO FLORIDA

UCF

UCF

Florida Power Electronics Center



Walt Disney World.

Florida Power Electronics Center

UCF

Dr.Issa Batarseh – Director
Dr.Wenkai Wu – Asst Director
Dr.Shiguo Luo – Asst Director (ret.)
11 Graduate Students

- Power Factor Correction (PFC) Circuits - NASA
- Soft-Switching DC-DC Converters - Florida and Industry
- Low voltage AC-DC and DC-DC Converters - NSF
- Dynamic Modeling and Control - NSF
- Electromagnetic Interference and Compatibility - NSF
- **Inverter Application / Fuel Cell, Photovoltaic Cell - Florida and Industry**
- High Frequency AC DPS - NSF & Florida

Fuel Cell Overview

Operation *Invented in 1838*	:	**Fuel cells force two fuels (H & O) to produce electrical energy by means of chemical reaction. *Unlike combustion engines, no moving parts and unlike batteries, no charging required***
Classification	:	***Based on electrolyte employed:* Phosphoric Acid (PA), Proton Exchange Membrane (PEM), Molten Carbonate (MC), Solid Oxide (SO), Alkaline, Zinc-Air (ZA)**
DC Output	:	1~2 V/**Cell, hence stacking is required.**
Efficiency	:	**Fuel Cells have 40% efficiency and could reach 80% in co-generation**
Control	:	**Fuel Cells can operate with or without regulated fuel flow to the stack, i.e. constant or variable fuel flow.**
Benefits	:	**Environmental Friendly and quite, Efficient, Cogeneration, Distributed Capacity, Fuel flexibility, Modular, Scalable, Federally Approved System**
Applications	:	**Stationary (Buildings, Hospitals,…), Residential (Domestic Utility), Transportation (Fuel Cell Vehicle), Portable Power (Laptop, cell phone), Landfill/ Wastewater treatment,..etc**

Residential Application Issues

- Fuel Cell based power distribution is viable solution for backup generation
- Prices are expected to drop at a much faster rate
- The distributed generation for residential application represents large size of market share
- Power electronic interface system are critical to the success of any residential power distribution application.
- The interface system must be inexpensive and reliable, small size and light weight.
- UPS applications to replace lead batteries (1/7 the size)
- Target of a maximum of $40/kW as a manufacturing cost

Portable Applications

- **There is a genuine economic demand for scaled down fuel cell designs to replace battery technology**
- **Multi billion dollar market share and unit sales of portable electronics device on the rise**
- **Ever increasing burden on battery life**
- **Increased portable device complexity and application flexibility with more power requirements.** ***Example: cell phones with added features such as Wireless Application protocol (WAP)***
- **The distributed generation for residential application represents large size of market share**

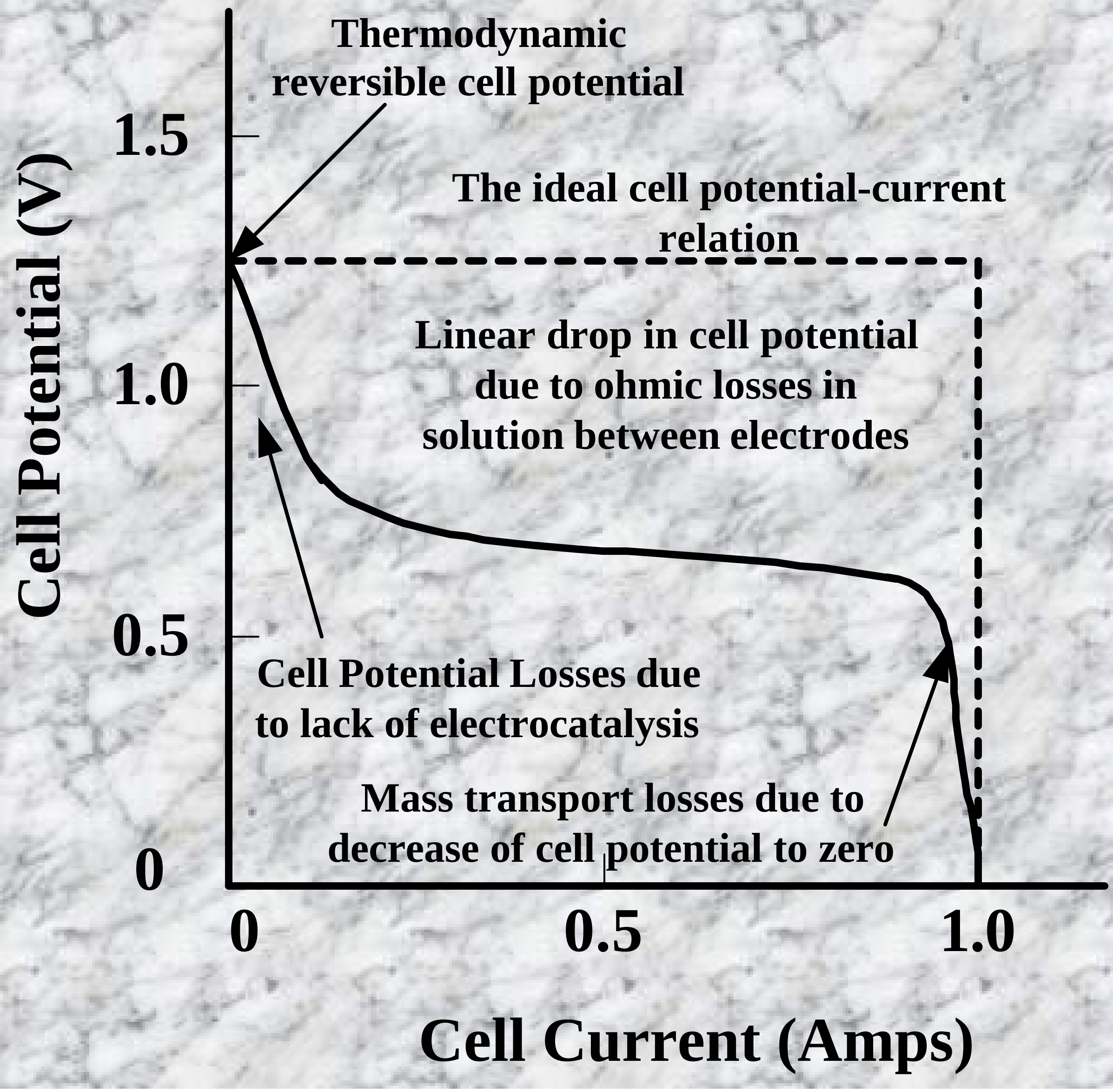
Fuel Cell Technical Issues

I) Basic physical understanding of Fuel Cells:

- **Fuel Cell Modeling to determine the optimum operating conditions**
- **Fuel Cell reaction to load changes, thermal transients**
- **Understanding operational difficulties involving fuel cell stacks and it's V-I characteristic curve.**
- **Filtering requirements due to strict current ripple specifications**
- **Fuel cell Stack and it's auxiliary systems such as:Air compressor, water cooling, valve to control fuel flow, humidifiers**
- **Understand Power Consumption in Auxiliary Systems**

V-I Characteristic of Fuel Cell

UCF



Fuel Cell Technical Issues

II) The Interface System

- Inverter Design Consideration
- Battery Backup Consideration
- Fuel Cell Protection Consideration
- Setup theoretical and physical measurement systems
- Size, weight, cost, reliability issues (for residential and other applications)

III) Factors affecting the coupling between Fuel Cell and the power Inverter :

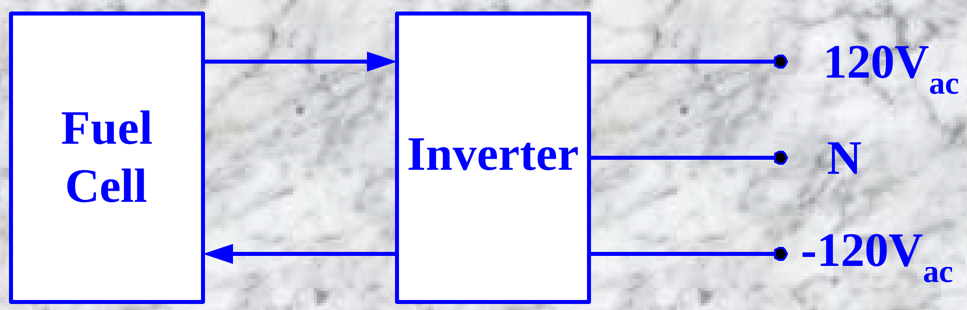
Standalone

- Fuel Flow regulation
- Battery Backup

Grid Tied

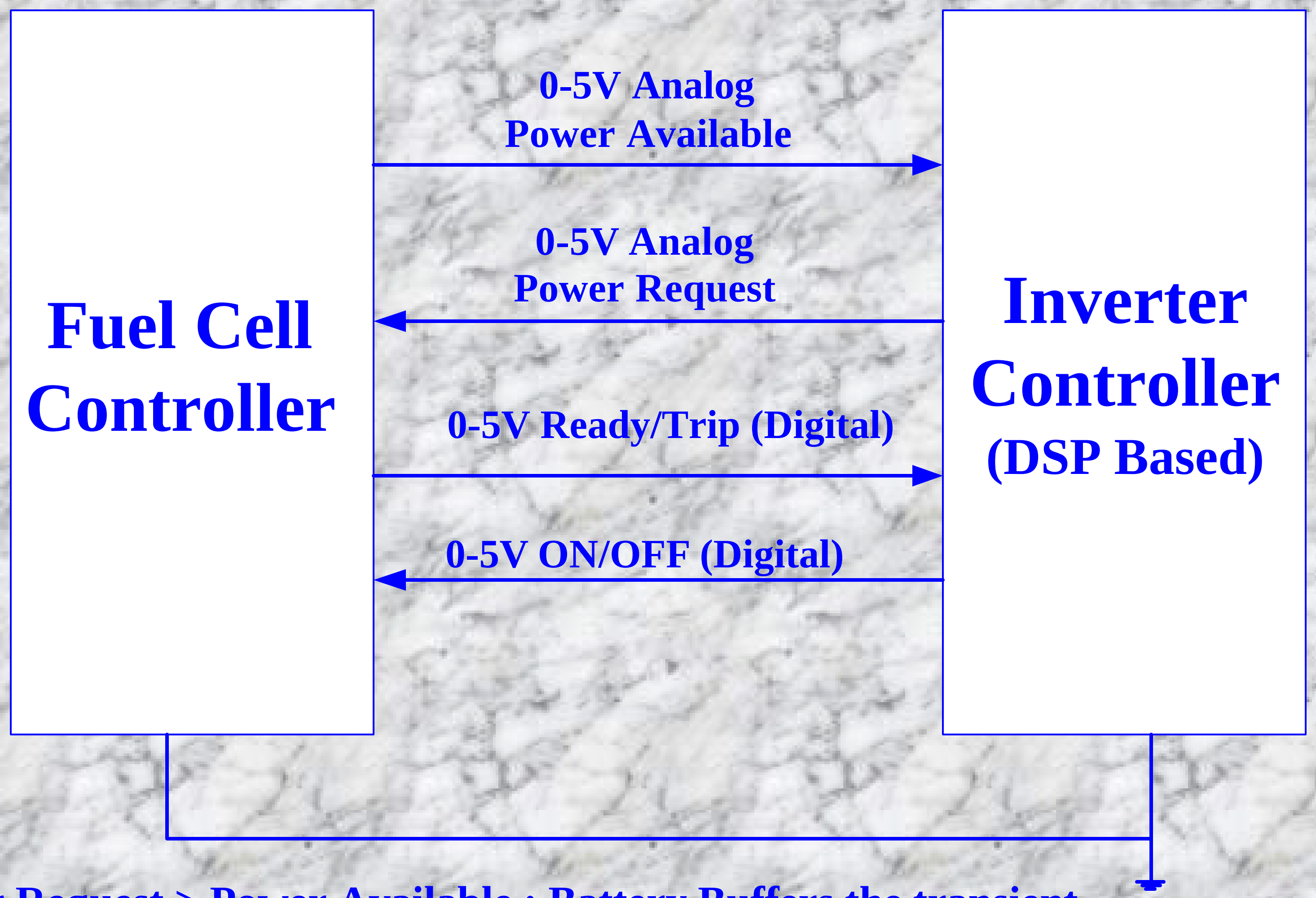
- Fuel Flow regulation
- Synchronization to grid

2001 Future Energy Challenge as a design example



- Uses the Proton Exchange Membrane (PEM) type fuel cell
- Uses Hydrogen Gas. Operating temperature 60-100^o C
- Fuel flow regulation system to fully utilize the consumption of hydrogen as it reacts to changing load demand
- Nominal 48V. Range 42-72 V
- 1.8kW power testing
- Open circuit voltage 72 V
- Slow response time (chemical v/s electrical process)

Handshaking Signals



If Power Request > Power Available : Battery Buffers the transient
If Power Request < Power Available : H_2 flow is reduced
Battery is used for start-up.

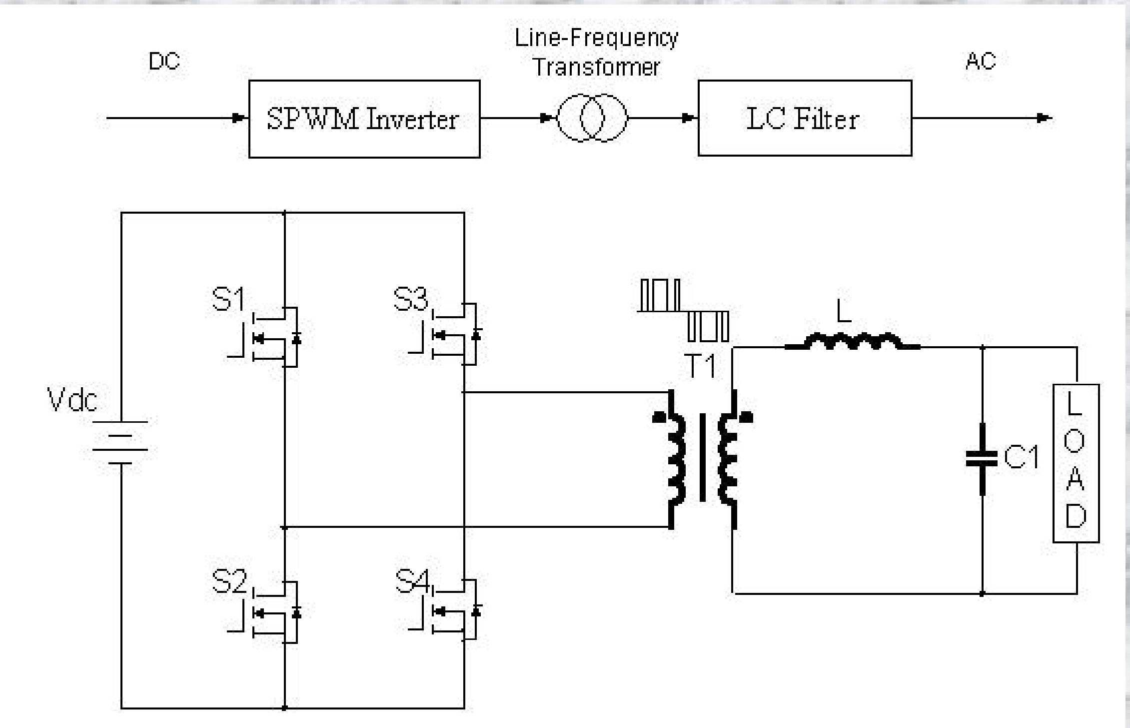
* Source : FEC2001

Review of the existing inverter topology

Conventional sinusoidal output inverter topology solution

<u>Disadvantages</u>

- **Bulky transformer.**
- **Large volume, High cost.**

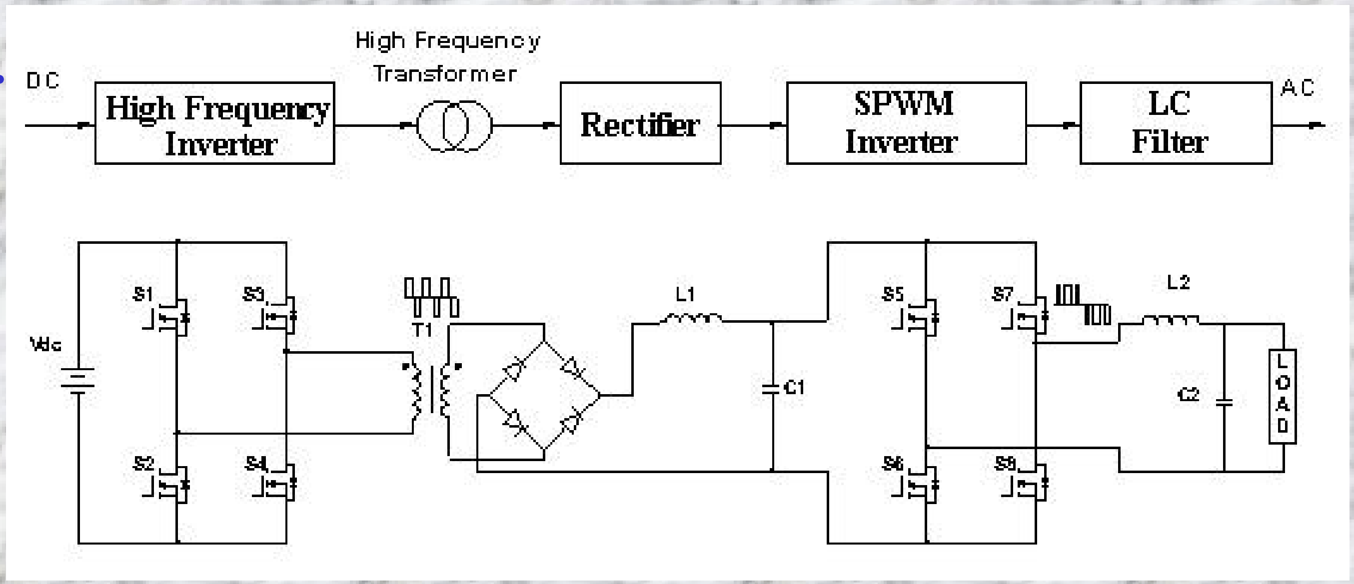


Review of the existing inverter topology

Improved sinusoidal output inverter topology solution

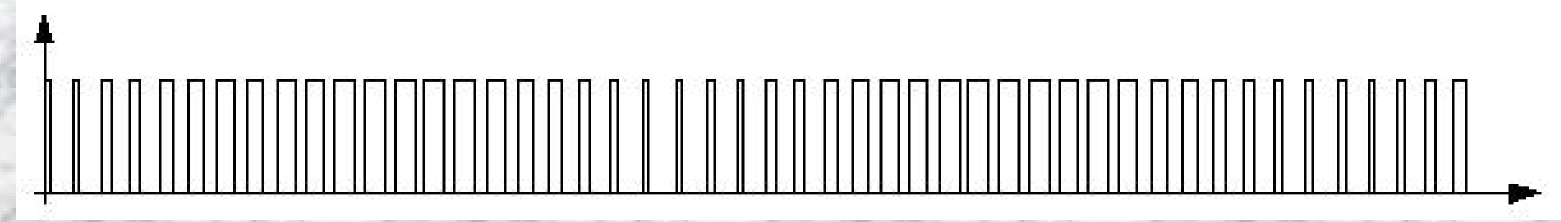
Disadvantages

- Complex Structure.
- High cost.
- Low Efficiency.

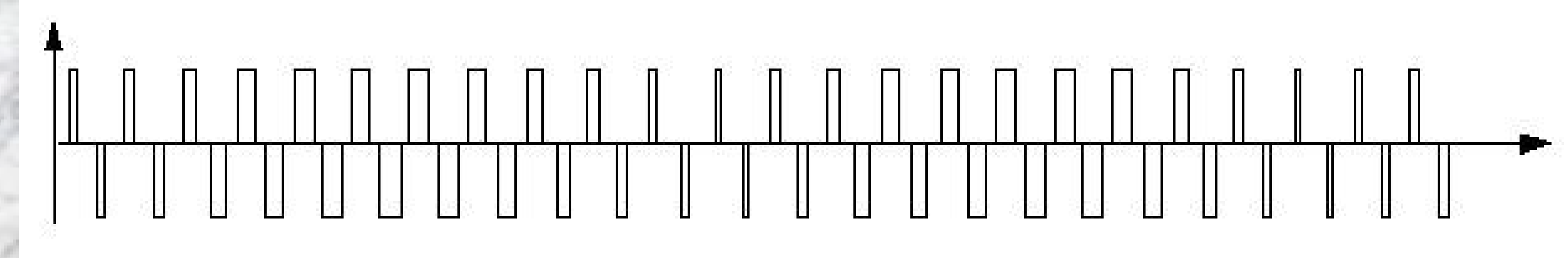


Concept of High Frequency Link Transmission Technique

The objective is to reduce the size of transformer by stepping up the switching frequency



The conventional bipolar SPWM waveform with low frequency component (the reference) included



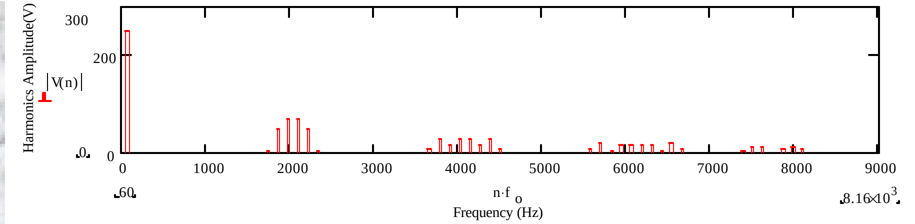
High frequency link technique transforms the conventional SPWM waveform into high frequency format, small sized transformer is allowed

Concept of High Frequency Link Transmission Technique

The theoretical analysis of the harmonics

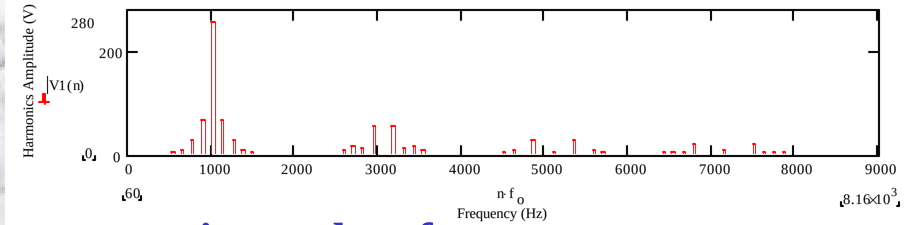
The conventional SPWM waveform transmitted by bulky line frequency transformer (fc=2kHz, fr=60Hz)

$$V(n) = \sum_{i=1}^{k} (\frac{2V_{dc}}{np}) \sin(n \frac{q_w(i)}{2}) \left\{ \sin\left[n(q_w(i) + \frac{q_w(i)}{2}) \right] - \sin\left[n(q_i(i) + \frac{q_w(i)}{2} + p) \right] \right\}$$



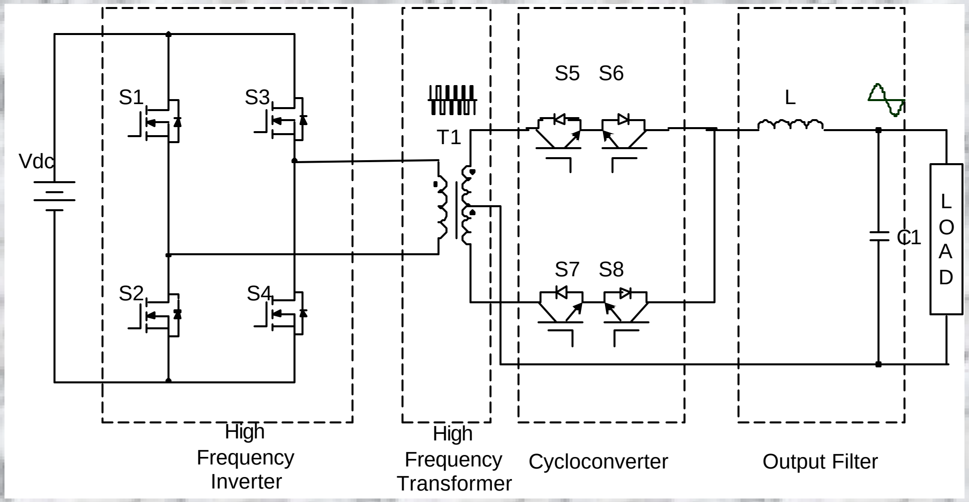
The waveform transmitted by compact high frequency transformer (fc=2kHz, fr=60Hz)

$$V(n) = \sum_{i=1}^{k} (-1)^i (\frac{2V_{dc}}{np}) \sin(n \frac{q_w(i)}{2}) \left\{ \sin\left[n(q_w(i) + \frac{q_w(i)}{2}) \right] - \sin\left[n(q_i(i) + \frac{q_w(i)}{2} + p) \right] \right\}$$

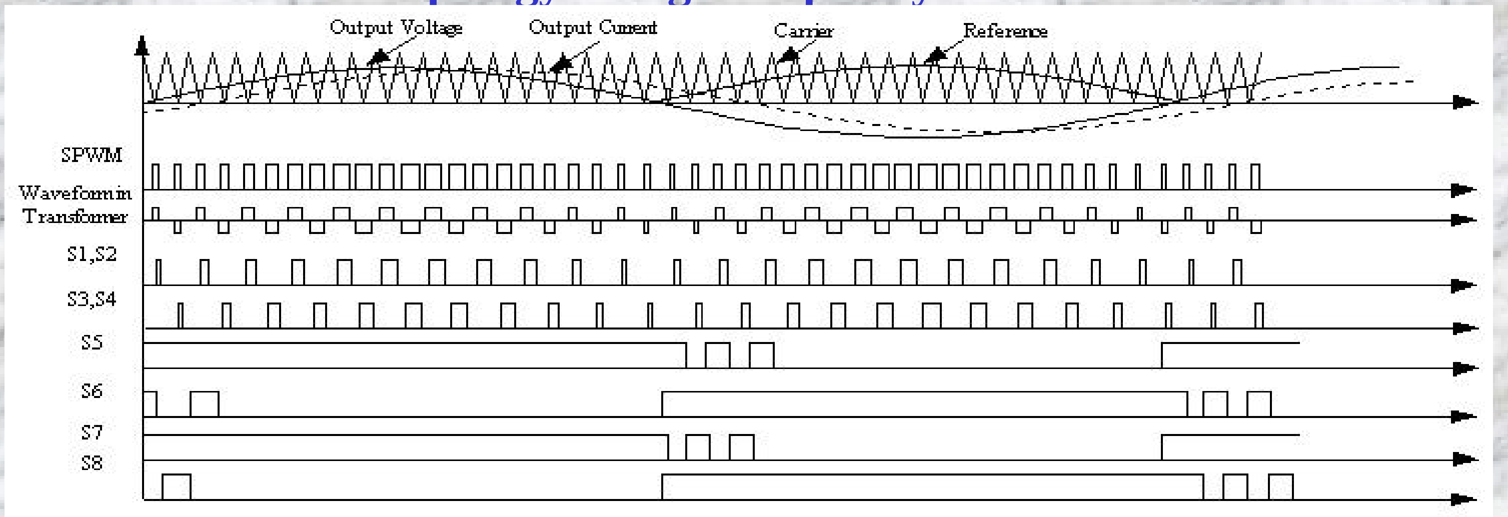


Since the waveform contains no low frequency component, a compact transformer is suitable for power transmission.

The Proposed Inverter Topology



The topology of high frequency link inverter

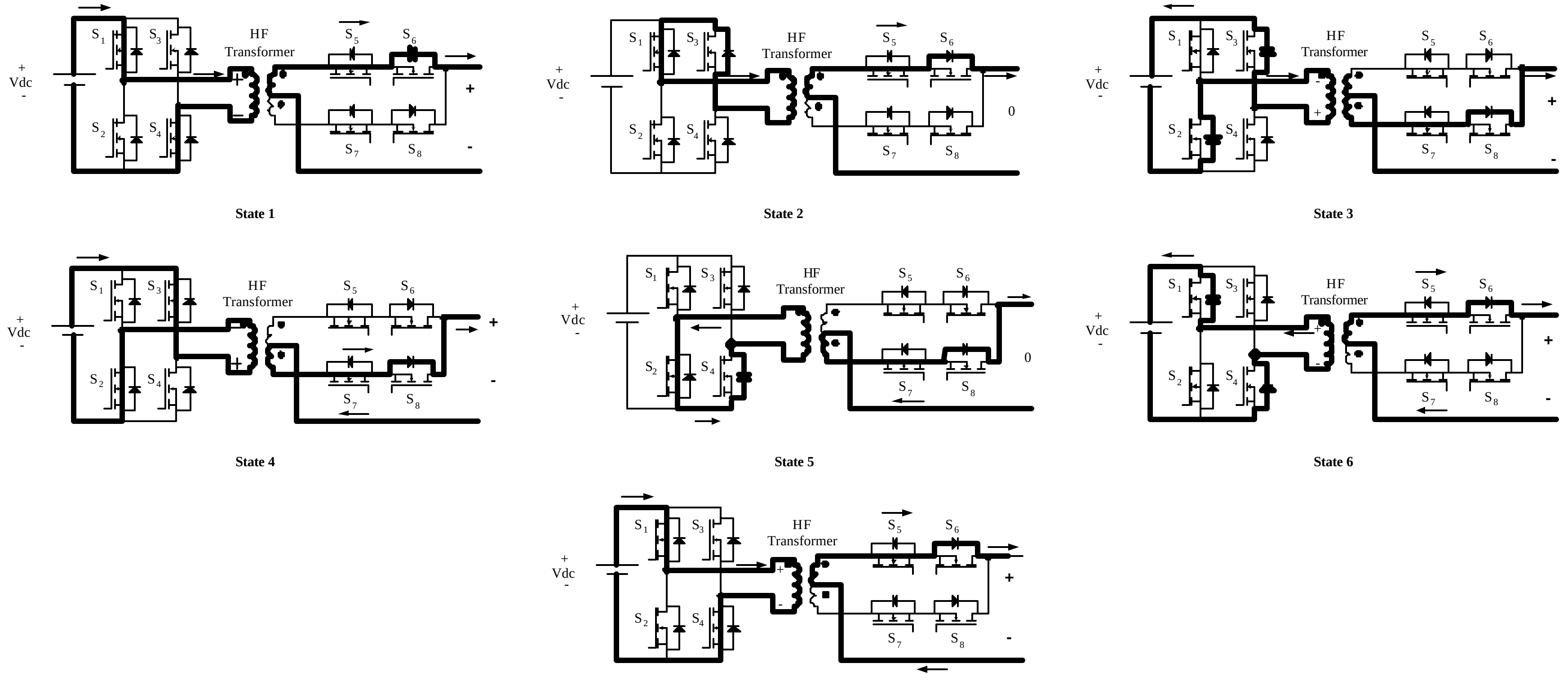


Drive Signal

Characteristics of the High Frequency Link Inverter

- No low frequency component exists in the waveform transmitted by transformer. A compact high frequency transformer is allowed for the transmission.
- The four switches in the secondary side of the transformer is operated mostly in line frequency which leads to low switching loss and high efficiency.
- The phase-shift control is used for the full bridge to realize the ZVS turning of the switches. The switching loss is greatly reduced compared with the conventional control scheme.
- Simple structure, lower loss and higher efficiency.

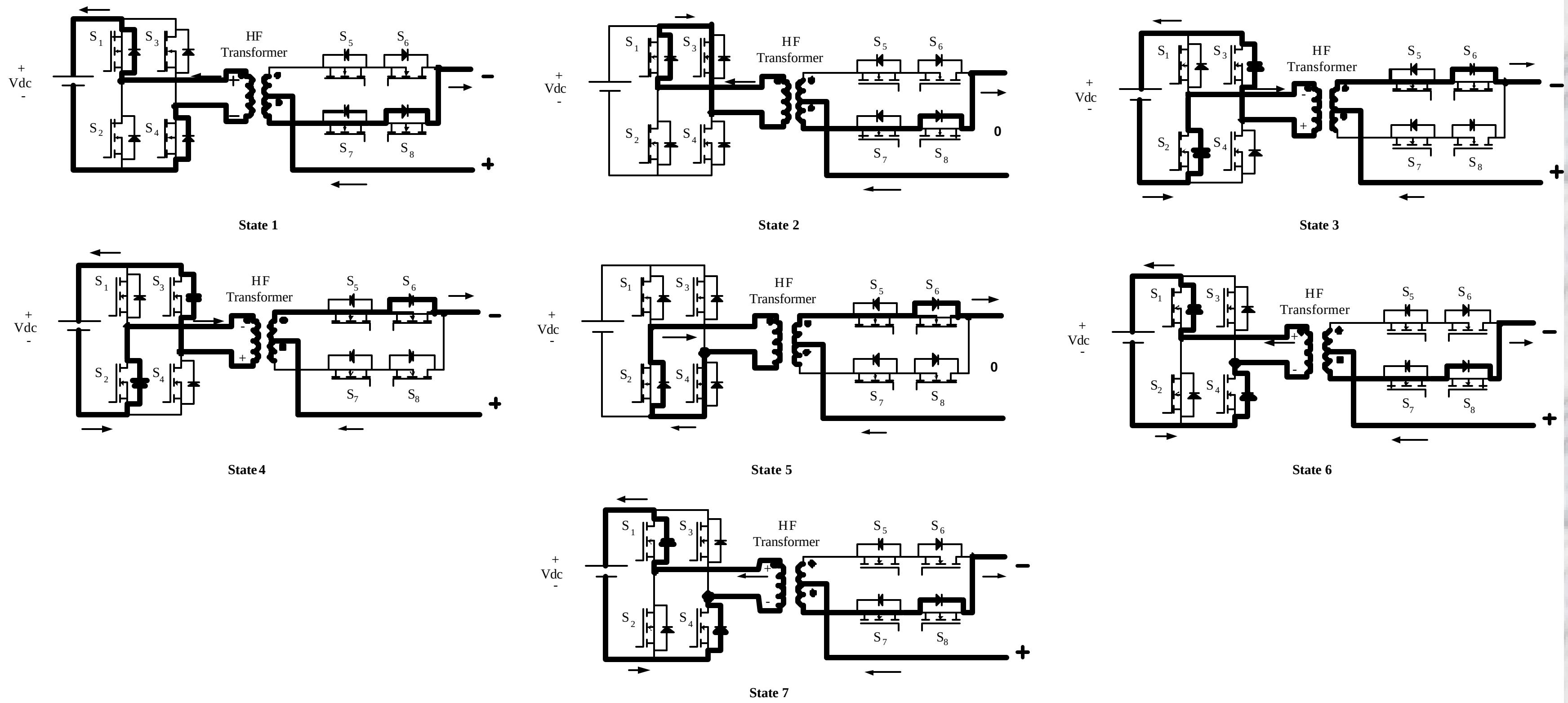
Operation Mode Analysis



State 1 State 2 State 3 State 4 State 5 State 6 State 7

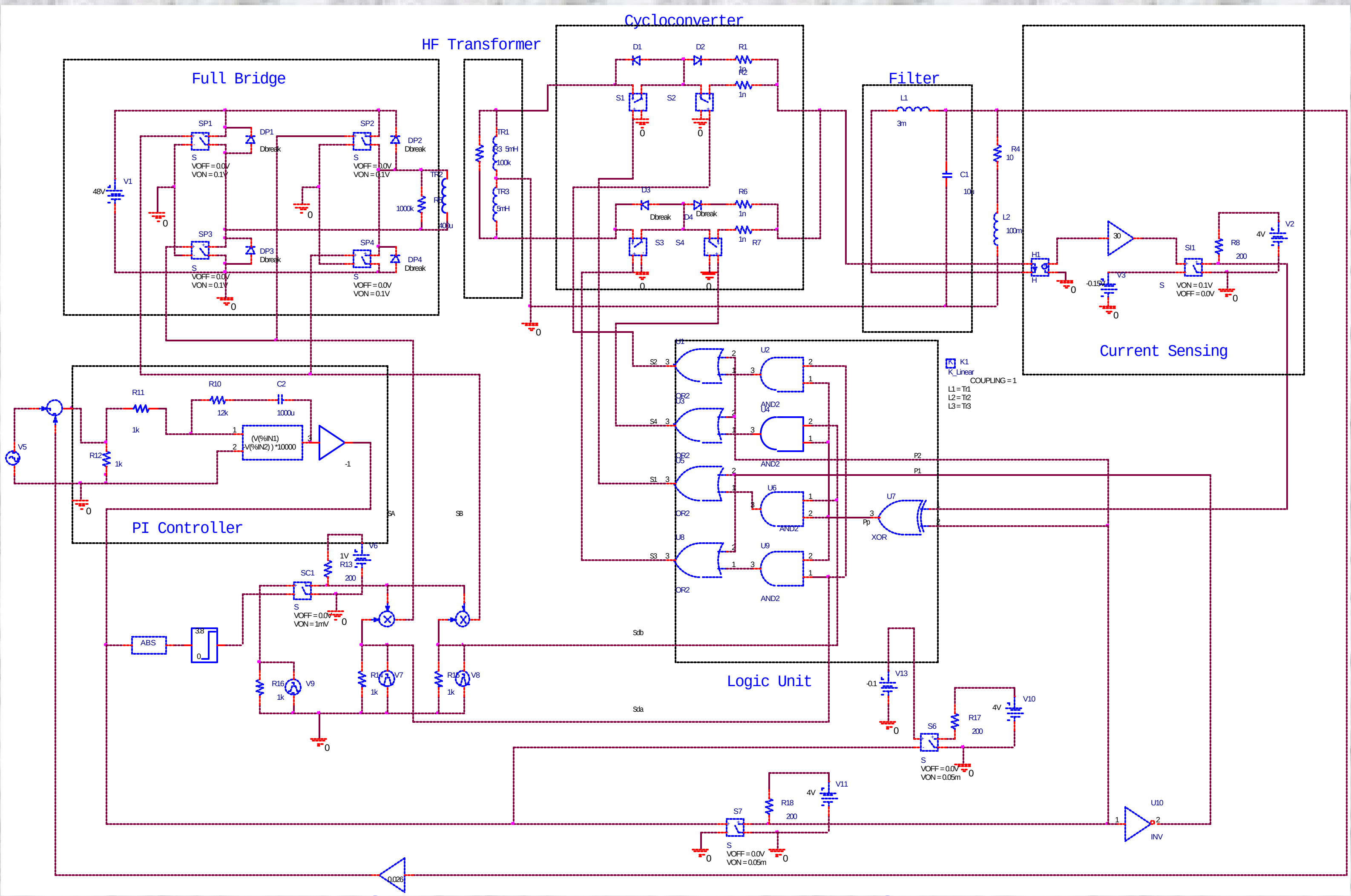
Duration I: positive output voltage, positive output current.

Operation Mode Analysis



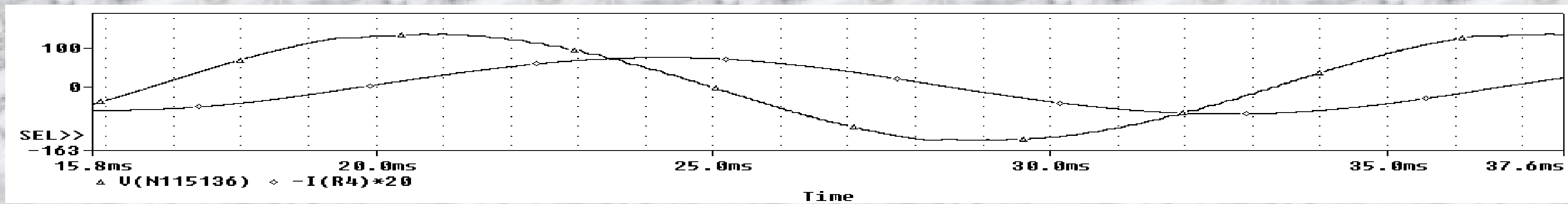
Duration II: negative output voltage, positive output current.

Simulation Circuit



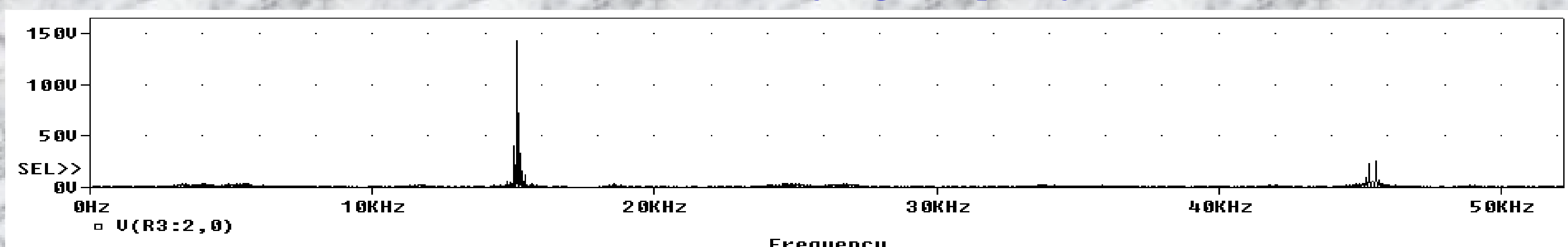
Power stage includes full bridge inverter, HF transformer, cycloconverter and output filter. Control circuit includes output current&voltage sampling, PI controller and logic unit.

Simulation Result



Output voltage and current

Waveform transmitted by high frequency transformer



Spectrum of the waveform through transformer(Switching Frequency: 30kHz)

The spectrum of the transmitted waveform shows that only high frequency component exists. Therefore, a compact high frequency transformer can be used for power transmission.

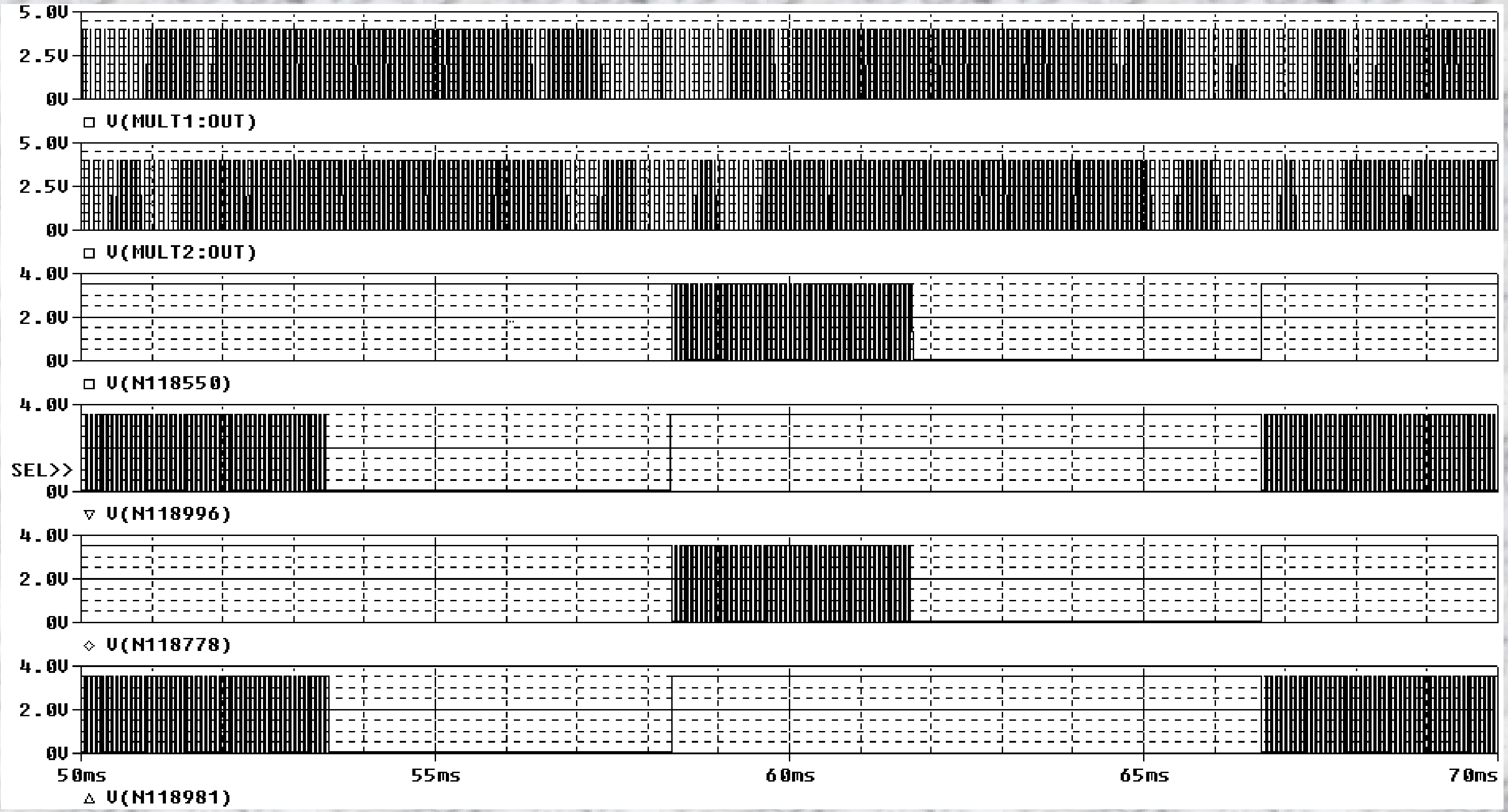
Output Voltage Waveform Harmonic Analysis

Harmonic No.	Frequency (Hz)	Fourier Component	Normalized Component
1	60	1.477E+02	1.000E+00
2	120	4.610E-02	3.122E-04
3	180	1.539E+00	1.042E-02
4	240	7.458E-02	5.051E-04
5	300	1.371E+00	9.282E-03
6	360	6.627E-02	4.488E-04
7	420	4.768E-01	3.229E-03
8	480	1.007E-01	6.816E-04
9	540	9.267E-01	6.276E-03
10	600	7.593E-02	5.142E-04

Total Harmonic Distortion (THD)= 2%

The close loop control provides clean output voltage waveform.

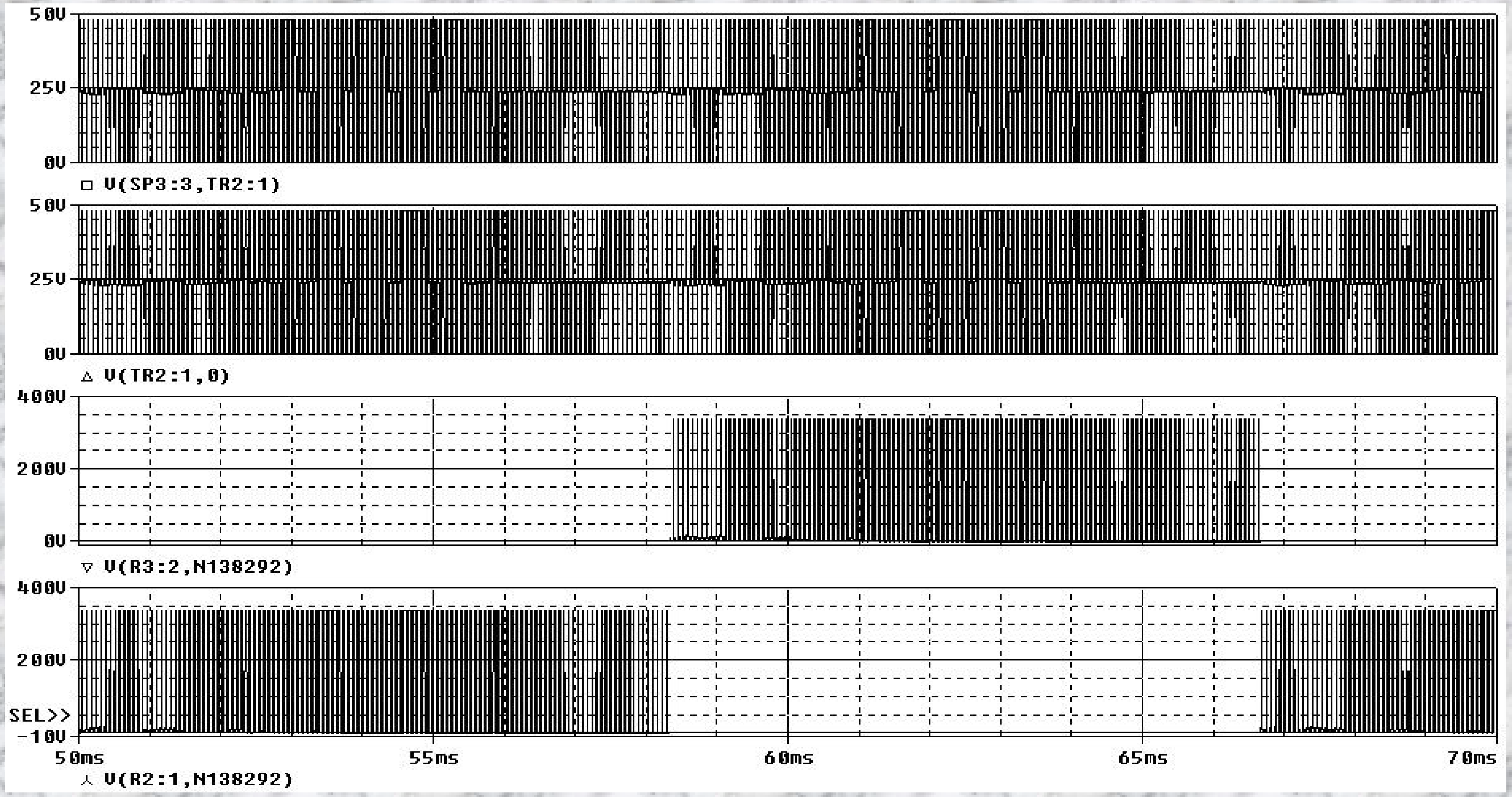
Simulation Result (Con.)



Drive Signal: (Switches in the primary side and secondary side)

The secondary side switches operated partly at line frequency which reduced the switching loss generally.

Simulation Result (Con.)



Voltage across the switches

No huge spikes found across the switches.

Design Specifications for Inverter

Output power rating	400W continuous, single phase.
Output voltage	120V nominal
Output Frequency	60 Hz ± 0.1 Hz.
Carrier frequency	42kHz
Input source	Nominal rating of 48 V dc.
Overall efficiency	Higher than 90% for resistive load.
Total harmonic distortion	Output voltage THD: less than 5% when supplying a standard nonlinear test load

Device Used for the prototype

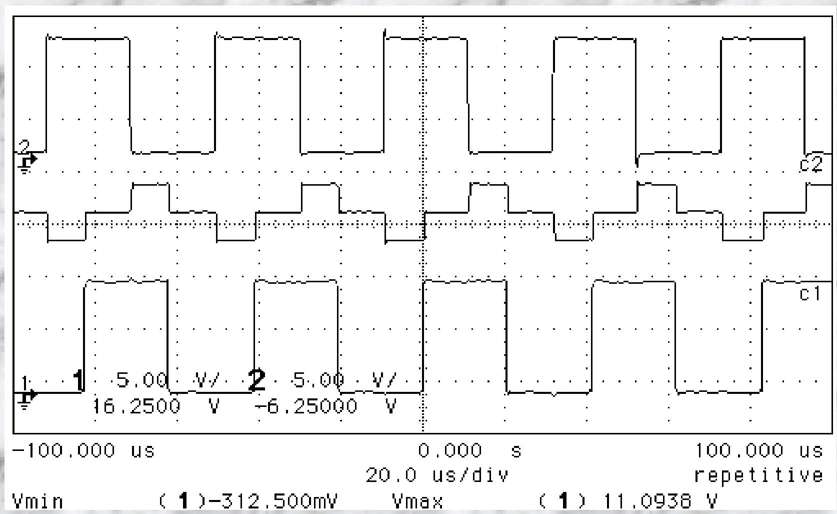
Power stage:

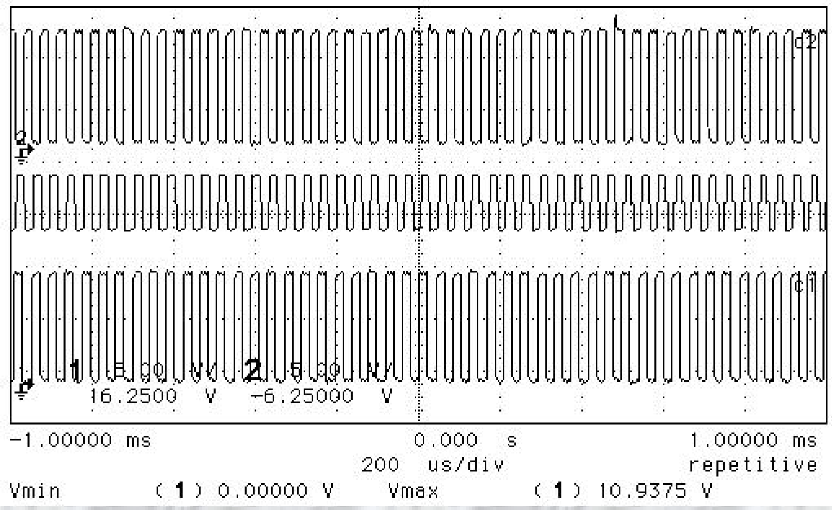
Primary full bridge	MOSFET SSH10N90A
Secondary side	IGBT IRG4BC30UD
Transformer	Center tapped at the secondary side

Control circuit:

Phase shift controller	UC3875 phase shift controller for full bridge
Driver IC	IR2110 for primary full bridge UC1708J for secondary cycloconverter
Optoisolator	4N25 for the cycloconverter driver

Experimental Result

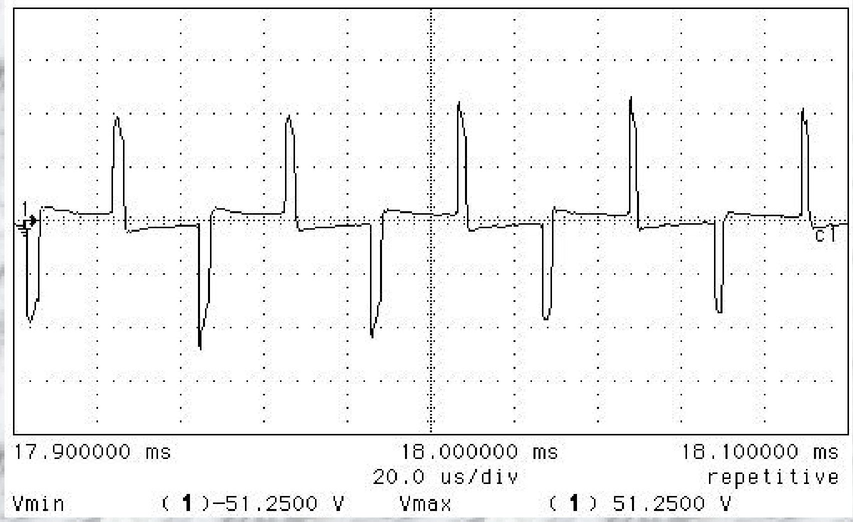


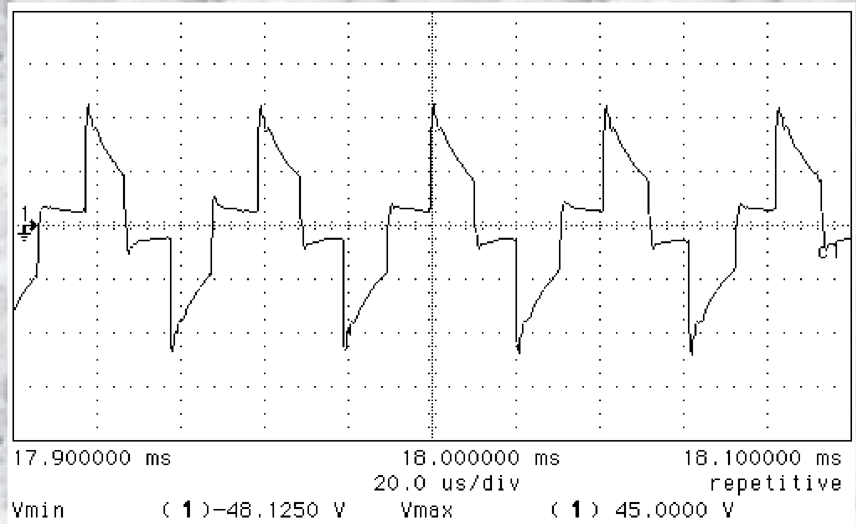


Phase-shift control signal for the full bridge in the primary side

Phase-shift control enable the switches in the full bridge operated at ZVS, the switching loss is greatly reduced

Experimental Result (Con.)

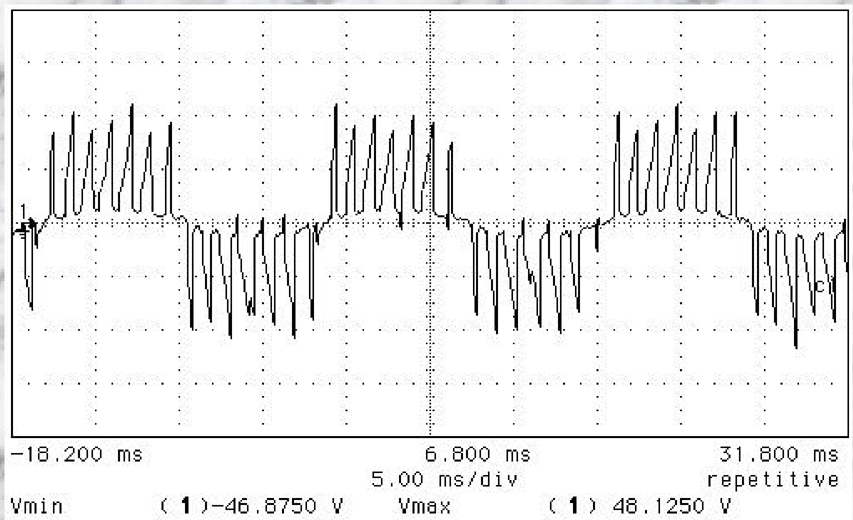


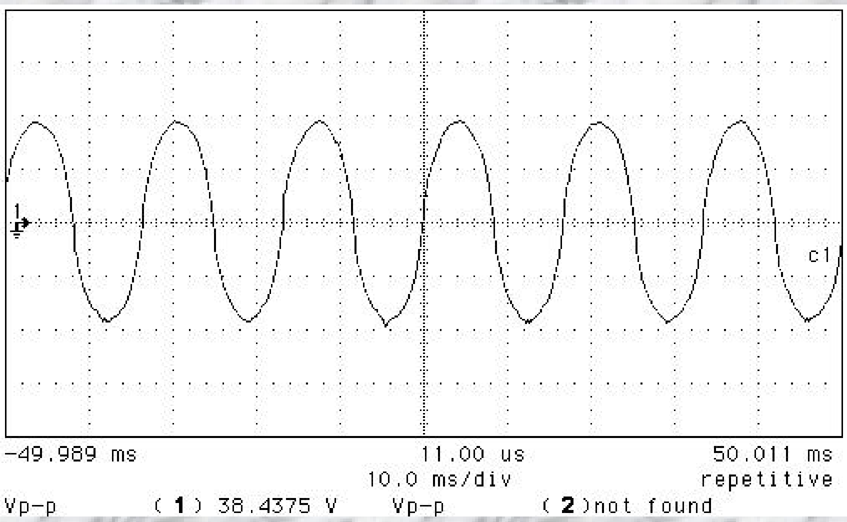


Waveform transmitted by HF transformer

The waveform contains no low frequency component which facilitate the power transmission

Experimental Result (Con.)





The unipolar SPWM waveform and the output voltage waveform

The output filter converts the unipolar SPWM pulse series into the sinusoidal output waveform

The future for cycloconverter in fuel cell application

- The phase shift control scheme enable the switches shift at ZVS, the total switching loss is generally reduced. The cycloconverter enable the swtiches operated mainly at line frequency. The switching loss dropped furtherly. The whole system efficiency is high compared with the conventional cycloconverter system.
- The high frequency operation reduced the size of the transformer, the whole system size is greatly reduced.
- The front side communication between the inverter and the fuel cell enable them work in harmony in the case of load variation.
- No high component current and voltage spikes. Together with the low loss of the switches, the inverter is expected to handle high power and suitable for high power applications.

How to accelerate the deployment of fuel cell distributed generation for home applications ?

- **Increased funding and awareness programs by state and federal agencies.**
- **Industry must play a major role in funding fuel cell based projects and pursue aggressive fuel cell R&D strategies.**
- **Educational campaign is needed to generate student interest in fuel cells** ***(example: Future Energy Challenge)***
- **Fuel Cell experts need to speak more.**
- **Increase the role of professional organizations (IEEE,IEE…etc) to promote special issues on fuel cell applications, modeling, inverter design,…etc**

Research Focus at UCF

- **Develop an understanding of Fuel cell modeling**
- **Identify and understand issues that affect the coupling between the fuel cell and the power inverter.**
- **Explore new inverter topologies and suitable controls**
- **Expand the above finding to similar sources like photovoltaics**
- **Participate in FEC 2003 Inverter Competition.**
- ***Minor detail:* $$$ - *Secure funding* - $$$?**

FEC2003 Inverter Specifications for UCF

• Input Voltage :	22-41 VDC, 29 VDC nom. ,275 A max. from fuel cell.
• Output Voltage :	120 V/240 V nominal (split-phase)., 60 Hz ± 0.1 Hz.
• Output power capability – nominal :	10 kW continuous, total (5 kW continuous @ displacement factor 0.7, leading or lagging, max.
• Output voltage harmonic quality :	(THD) - less than 5% when supplying a standard nonlinear test load
• Maximum input current ripple :	3% rms of rated current
• Overall energy efficiency :	Higher than 90% for 5.0 kW resistive load with minimal efficiency degradation up to peak power and down to minimum power.
• Protection :	Industry standard
• Communication interface :	Control communication between fuel cell and inverter is through RS232
• Manufacturing cost :	Less than US$40/kW for the 10 kW design in high-volume production.

Concluding Remarks

- **Many years have been invested in fuel cell research and development in federal and industrial Labs!**
- **Fuel cell research and funding activities are in the increase.**
- ***DOE FY 03 Fuel Cell Budget $104.5 Million***
- **The US market is expected to reach $3 billion next year.**
- **No doubt Fuel Cell will continue to emerge as an important source of clean energy for residential applications.**
- **2kW – 10kW covers the residential segment and 40% of US power consumption is domestic.**
- **Hence with the availability of alternate power sources, we need very inexpensive, reliable power interface systems.**
- **These systems can be used to provide solution for remote power generation, backup generation and distributed generation.**
- **With more than 2 billion people without grid power, connecting Fuel Cell powered sources to the grid will continue to grow and give a boost to the concept of net metering.**
- **Fuel cell installed annual generating capacity is currently 1.5-2 GW and expected to reach 15GW in the next few years.**
- **Projected global demand for transportation fuel cell will reach $9 billion in 2007.**