High Frequency Inverter
Design Fundamentals

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Agenda

By the End of this session we will...

- Understand different kinds of back up systems
- Discuss building blocks of basic inverter
- Discuss the evolution of the inverter topologies
- Understand bi-directional inverter
- List merits and de-merits of each type of inverter
- Understand how high frequency inverter addresses the short-falls of conventional inverter
- Discuss design intricacies of high frequency inverter
- Understand processor requirements of HF inverter
Basic building blocks of an inverter

Input → AC-DC Bat Charging → Bypass path → DC-AC, Inverter → Output

Input voltage directly switches the change over relay
Inverter? UPS? confusion

**Inverter**
- Change overtime >= 10 ms

**UPS Line interactive**
- Change overtime < 10 ms

**UPS Online**
- Change over time = 0
Early inverters (Design-1)

Bypass path

Input voltage directly switches the change over relay
Merits and de-merits of this topology

• Very Simple design. Many earlier designs did not even have a PCB!
• Uses 2 transformers; expensive and bulky
• Yet, only one transformer is in use at a time
• No intelligent element in the design, Most operations happen by preset parameters
• Un-controlled charge and discharge cycles
• Not a closed loop system to ensure stable output
• Signal generator is usually a multi-vibrator and the output is not a pure sine wave.
• Early designs used transistor banks which were prone to failure
Bi-directional inverter topology (Design-2)

Input

Transformer

Rectifier

Regulator

Signal generator

Amplifier

Transformer

Intelligence: uC/DSC

Output

Input
Changes from Design 1 to Design 2

- Addition of an intelligent element i.e., uC or DSC
- Pure sine wave generated by PWM technique
- One of the transformers eliminated
- Addition of DSC/uC enables a variety of new useful functions
- Synchronous transition of load from Mains to Inverter and vice-versa
- Closed loop control implemented through software
- Intelligent protection mechanisms implemented thro’ software
PWM Technique

$V_{spwm.1} \quad NV_B$

$V_{spwm} \quad \sqrt{2220V}$
Example implementation: Bi-directional topology

• A very simple topology, almost all the building blocks are bi-directional
• Digital signal controller (not shown in the picture) manages the charging, discharging and signal generation by manipulating the gate drives of the switching elements
• DSC Generates pure 50 Hz sine wave using PWM technique
• Software can control output voltage, wave shape, frequency etc in real time.
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What we need from a DSC to do all these?

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Merits and challenges of bi-directional topology

Merits:

• Cost reduction due to elimination of 1 transformer
• Addition of a Digital signal controller gives more flexibility and control to designers
• Enables implementation of additional features and protection mechanisms

Challenges

• Increased complexity
• Processor working in a noisy environment needs effective noise isolation
• Transformer is used as a bidirectional device. Copper losses during charging cycles are very high compared to earlier design-1 topology
Need for improvements

Bi-directional Inverter design has three drawbacks

1. Poor energy efficiency during charging cycles due to higher iron losses has to be overcome

2. Still heavy and bulky due to transformer. Expensive to build and expensive logistics. Need a lighter solution

3. Noisy operation as the inverter transformer operates at 50Hz (audible frequency)
A new topology !!!

• How to address these needs?
• How to build a solution brick by brick?
• Should we stick to bi-directional topology?
• Advent of High frequency inverter
• New challenges!!
Battery charger:

- Battery charger is essentially a regulated DC power supply which can operate in constant current and constant voltage modes as desired.
- The voltage, the current, when to operate in which mode is defined by the type of the battery and the battery voltage.
- Regulator should be able to dynamically switch between the modes.
- Switch mode power supplies can fulfill these requirements, and this also operates at high frequency (20KHz- 200KHz), Hence no audible noise.
- Health monitoring can help improve battery life and performance. Help of a Digital signal controller comes in handy.
Example Battery charging cycle

Lead-Acid battery
• Pulse width is controlled by Digital signal controller so that the required voltage and current are achieved as per the battery specifications.
• Charging voltage and current are measured thro’ ADC inputs of the digital signal controller. A closed loop control is implemented in software.
How to make 230V AC from 12/24V DC?

... well without the transformer being bulky and noisy

- Generate 12/24AC 50Hz signal from 12/24V DC
- Amplify to required power
- Step up 12/24V to 230V

Vs

- Step up 12/24V DC to $\sqrt{2} \times 230V$ DC
- Shape 50Hz wave from $\sqrt{2} \times 230V$ DC
Step-up: Battery booster

- Generate PWM to drive the switching elements (MOSFET)
  - PWM block of DSCs are useful to generate the PWMs
  - Higher frequencies between 20KHz to 200KHz can be used
- Step up with a high frequency transformer
  - Higher frequency transformers are smaller and lighter compared to their 50Hz counterparts
  - PCB mounted transformer can be used
- Convert back to DC with simple rectifiers
  - Rectified output should be $\sqrt{2} \times 230V$
  - Use ripple filters as needed

Gates are driven by digital signal processor
High Frequency transformer

Before

After
Flux density, which is the key design factor of a transformer, is a function of both cross sectional area of the core and frequency.

\[
B_{\text{max}} = \frac{V_{\text{rms}} \times 10^8}{4.44N \times Ac \times F} \quad \text{for sine waves}
\]

\[
B_{\text{max}} = \frac{V_{\text{pk}} \times 10^8}{4N \times Ac \times F} \quad \text{for square waves}
\]

In this equations: \( V \) - voltage (volts), \( N \) - winding's turns, \( Ac \) - core's cross-sectional area (sq.cm), \( F \) - frequency (hertz)

 Desired flux density can be achieved by reducing the cross sectional area of the core but increasing the frequency.

For a given wattage, the ferrite core HF transformers operate with lower flux densities than the Iron core transformers.
50 Hz Sine wave shape using PWM

- Generate PWM to drive the switching elements
  - PWM block of DSCs are useful to generate the PWMs
  - Higher frequencies between 20KHz to 200KHz can be used
  - High voltage MOSFETs or IGBTs are used for the switching bridge
    - Frequency of operation and output power decide the choice of IGBT or MOSFET
    - Gate drive circuitry has to be galvanic isolated from the digital plane
- A low pass filter at the output produces continuous sine wave from PWM signal

Shape 50Hz wave from $\sqrt{2} \times 230$V DC
Complete discharge path

DC input source

HF inverter

HF transformer

Diode rectifier

LPF

PWM inverter

AC output
### IGBT Vs MOSFET

**MOSFET**

- $P_{\text{cond}} = I^2 D(\text{rms}) \times R_{\text{ds(on)Hot}} \times D$
- $P_{\text{sw}} = I_d \times V_{\text{ds}} \times t_{\text{SW}} \times f_{\text{SW}}$
- **Negative thermal co-efficient**

**IGBT**

- $P_{\text{cond}} = V_{\text{ce(on)}} \times I_c \times D$
- $P_{\text{sw}} = E_{\text{ts(Hot)}} \times f_{\text{SW}}$
- **Positive thermal co-efficient**

- $f_{\text{SW}}$ - switching frequency
- $E_{\text{ts(Hot)}}$ - total switching losses (in data sheet)
- $t_{\text{SW}}$ - total switching time (on + off, in data sheet)
• PWM Switching elements are on the high voltage side of the transformer. It is not safe for DSC or any other low voltage digital circuit to share anything with this part of circuitry
• Individual ground references are required for each of the MOSFET/IGBT in the bridge
• MOSFET/IGBT are voltage switched devices. They can be turned on easily by applying the voltage to the gate. However, turning them off is tricky as they tend to retain the voltage at gate due to gate junction capacitance. Special effort should be made to turn them off.
Other necessary circuitry

- **Battery Charge and discharge current sensing**
  - Implemented using a very low value resistor, an inverting amplifier and a non-inverting amplifier and fed to the ADC inputs of the DSC
  - Charge current readings are used to control the constant current and constant voltage parameters of the charging circuitry

- **Battery voltage sense**
  - Implemented using a potential divider to scale the voltage and fed to the ADC input of the DSC
  - Necessary for controlling the charge cycles and deep discharge protection

- **Output voltage sense**
  - Implemented using a transformer and a full wave rectifier to scale down the voltage
  - Necessary for controlling battery booster PWMs and Inverter PWMs to ensure stable output voltage
Other necessary circuitry … cntd

- **Mains voltage sense and Zero cross sense**
  - Mains sense implemented using a transformer and a full wave rectifier to scale down the voltage
  - Necessary for controlling change over relay in the event of mains failure
  - Zero cross sensors are implemented using voltage comparators in conjunction with mains transformer
  - These signals help the DSC to know whether the main is in positive or negative cycles. This is essential for synchronous transfer of load from mains to inverter and vice versa

- **DC-DC converters/LDOs**
  - 5V DC and 3.3V DC needed for the operation of Op-Amps and the DSC are derived from battery voltage using either LDOs or DC-DC converters

- **Temperature sensor**
  - Implemented using a thermister, and connected to DSC, Used to protect MOSFETs/ IGBTs from over-heating
Other necessary circuitry … cntd

- Change over relay
  - Instrumental in transition of the load between the mains supply and the inverter output

- Isolated DC sources
  - 3 isolated DC sources with independent ground references are required to power each of the 4 MOSFET/IGBT gate drivers. Both the low-side IGBT gate drivers may share the same supply as they share the same net for the source pins.
  - can be implemented by adding 3 additional 15 V secondary windings in the main transformer.
Bells and whistles…

- **LED / LCD display**
  - Useful as user interface to convey the status of the system visually

- **Audio alarm**
  - Useful as user interface to convey the status of the system visually

- **Front panel switch**
  - To switch the system between various modes

- **USB/Serial interface**
  - Provide computer connectivity; can be used for remote management, data logging, etc…
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Recommended devices from Freescale

http://www.freescale.com/webapp/sps/site/homepage.jsp?code=DSC_HOME
About Magphy… www.magphy.com

- **Magphy Expertise**
  The Magphy team has a strong background of designing complex embedded systems from past experience. We have contributed in designing many SBCs, telecom blades, media players and other embedded systems that are in service today, both in terms of hardware design and software development. Innovation and quality have been our forte as we have built our careers.

- **Magphy Experience**
  The Magphy team comes with a very rich experience in Embedded systems design. All in all, the current team has more than 50 man years of experience in this domain. We have a vast experience in providing industry standard solutions as well as custom specific solutions that are modular, scalable and efficient.

- **Magphy Focus**
  Magphy systems focus on the emerging Energy and automotive sectors. We believe that the emphasis, growth and growing technology content in these sectors promise growth of Magphy.

- **Magphy Founders**
  Magphy is floated by some of the very experienced Managers and senior engineers of the Embedded computing industry. We also share the common vision of providing high quality and cost effective solutions to the industry.
Thank you