Hardware-in-the-Loop Systems With Power Electronics – a Powerful Simulation Tool

Prof. Dr.-Ing. Ralph Kennel, Guangye Si
Technische Universität München
Electrical Drive Systems and Power Electronics
Hardware-in-the-Loop Systems

Simulation Computer

Product (part of real world)

reference values

real values
Hardware-in-the-Loop Systems

the „Hardware“, of course, could be simulated in the Computer as well

this requires, however, exact modelling ...

the „Hardware“, of course, could be simulated in the Computer as well

this requires, however, exact modelling ...

Simulation Computer

Hardware
(part of real world)

reference values
real values
Hardware-in-the-Loop Systems

Simulation Computer

Hardware (part of real world)

- Reference values
- Real values

It is simpler to use the "real world".

This requires, however, exact modelling...

TUM

IEEE Power Electronics Society
Hardware-in-the-Loop Systems

Simulation Computer

Hardware (part of real world)

It is simpler to use the "real world" especially with respect to the physical behaviour of energy!
Outline

- Introduction (Virtual Machine)
- Power Stage for High Switching Frequencies
  - Principle of Sequential/Interleaved Switching
  - Principle of Magnetic Freewheeling Control
  - Experimental Results
- Control of Virtual Machine
  - Problems with Standard PI Control
  - Possible Solutions
  - Successful “Machine Model”
- Summary

- Introduction (Virtual Grid)
- Power Stage for High Power and High Switching Frequencies
  - Connecting Inverters with different characteristics
- Control of Virtual Grid
  - Synchronous rotating frame (SRF) multi-loop PI controller
  - Stationary frame
    Proportional resonant (P+R) controller
  - Linear quadratic (LQR) optimal state space controller
- Experimental Results
- Summary
Outline

- Introduction (Virtual Machine)
  - Power Stage for High Switching Frequencies
    - Principle of Sequential/Interleaved Switching
    - Principle of Magnetic Freewheeling Control
  - Experimental Results
  - Control of Virtual Machine
    - Problems with Standard PI Control
    - Possible Solutions
    - Successful "Machine Model"

- Summary

- Introduction (Virtual Grid)
  - Power Stage for High Power and High Switching Frequencies
    - Connecting Inverters with different characteristics
  - Control of Virtual Grid
    - Synchronous rotating frame (SRF) multi-loop PI controller
    - Stationary frame Proportional resonant (P+R) controller
    - Linear quadratic (LQR) optimal state space controller
  - Experimental Results
  - Summary

... only if there is sufficient time!!!
Basic Idea: Virtual Machine

inverter under test

this is the „real world“

TUM

IEEE POWER ELECTRONICS SOCIETY
Powering a Sustainable Future
Basic Idea: Virtual Machine

Diagram of a power electronics system with an inverter under test, machine model, and PWM control.
Basic Idea: Virtual Machine

this is the "real world"

this is the "Hardware-in-the-Loop System"
Outline

- Introduction (Virtual Machine)
- Power Stage for High Switching Frequencies
  - Principle of Sequential/Interleaved Switching
  - Principle of Magnetic Freewheeling Control
  - Experimental Results
- Control of Virtual Machine
  - Problems with Standard PI Control
  - Possible Solutions
  - Successful “Machine Model”
- Summary

- Introduction (Virtual Grid)
- Power Stage for High Power and High Switching Frequencies
  - Connecting Inverters with different characteristics
- Control of Virtual Grid
  - Synchronous rotating frame (SRF) multi-loop PI controller
  - Stationary frame Proportional resonant (P+R) controller
  - Linear quadratic (LQR) optimal state space controller
- Experimental Results
- Summary
Outline

- Introduction (Virtual Machine)
- Power Stage for High Switching Frequencies
  - Principle of Sequential/Interleaved Switching
  - Principle of Magnetic Freewheeling Control
  - Experimental Results
- Control of Virtual Machine
  - Problems with Standard PI Control
  - Possible Solutions
  - Successful “Machine Model”
- Summary

- Introduction (Virtual Grid)
- Power Stage for High Power and High Switching Frequencies
  - Connecting Inverters with different characteristics
- Control of Virtual Grid
  - Synchronous rotating frame (SRF) multi-loop PI controller
  - Stationary frame Proportional resonant (P+R) controller
  - Linear quadratic (LQR) optimal state space controller
- Experimental Results
- Summary
Requirements
with respect to the power stage

• „Virtual Machine“ must provide **better performance**
  than the „inverter/device under test“

  to enforce **any** current reference
  provided by the model
  
  ➢ higher switching frequency \((> 50 \text{ kHz})\)
  ➢ slightly higher voltage \(U_{DC} (> 750 \text{ V})\)
Outline

- Introduction (Virtual Machine)
- Power Stage for High Switching Frequencies
  - Principle of Sequential/Interleaved Switching
  - Principle of Magnetic Freewheeling Control
  - Experimental Results
- Control of Virtual Machine
  - Problems with Standard PI Control
  - Possible Solutions
  - Successful “Machine Model”
- Summary

- Introduction (Virtual Grid)
- Power Stage for High Power and High Switching Frequencies
  - Connecting Inverters with different characteristics
- Control of Virtual Grid
  - Synchronous rotating frame (SRF) multi-loop PI controller
  - Stationary frame Proportional resonant (P+R) controller
  - Linear quadratic (LQR) optimal state space controller
- Experimental Results
- Summary
Basic Idea of Sequential Switching

sharing the switching losses between several IGBTs in parallel connection by switching them *sequentially*
Basic Idea of Sequential Switching

**switching frequency** of each *IGBT*:

\[ f_{\text{IGBT}} = \frac{f_{\text{parallel}}}{n} \]

- \( n \) = number of IGBTs in parallel connection

**switching frequencies**:

\[ f = 50...100 \text{ kHz} \]
Basic Idea of Sequential Switching

the devices are loaded with the **full current**!

- $f_{\text{ges}} = 1/T_{\text{PWM}}$
- $f_{\text{igbt}} = f_{\text{ges}}/3$

**Reduction of the switching losses by reducing the switching frequency in each device**

- Limitation of the **maximum switch-on time** to the **cycle time** of the system frequency
  - (pulse / pause = 33.3% max. for three IGBTs in parallel)
Problem: Free Wheeling Diodes

*free wheeling diodes* cannot be switched *in sequential order (actively)*

the following problems result from that:

• all (!) free wheeling diodes are *loaded* with the *full switching frequency*

• the *diodes* with the lowest voltage drop *heat more than the others !!!*
  
  ➔ *unsymmetric* load is *increased*
  ➔ parallel diodes

  are *not stable* in operation !!!
Outline

- Introduction (Virtual Machine)
- Power Stage for High Switching Frequencies
  - Principle of Sequential/Interleaved Switching
  - Principle of Magnetic Freewheeling Control
  - Experimental Results
- Control of Virtual Machine
  - Problems with Standard PI Control
  - Possible Solutions
  - Successful “Machine Model”
- Summary

- Introduction (Virtual Grid)
- Power Stage for High Power and High Switching Frequencies
  - Connecting Inverters with different characteristics
- Control of Virtual Grid
  - Synchronous rotating frame (SRF) multi-loop PI controller
  - Stationary frame Proportional resonant (P+R) controller
  - Linear quadratic (LQR) optimal state space controller
- Experimental Results
- Summary
Basic Idea of Magnetic Freewheeling Control
Diode Current Measurement in a Half Bridge with sequential Switching of Power Devices

\[ U_{DC} = 600 \, \text{V} \]
\[ I = 25 \, A_{\text{peak}} \]
Magnetic-parallel coupling of identical inverters

- Magnetic coupling (Freewheeling control)
  - Diodes of standard module without control capability
  - Solution: coupling inductors
    - $L_\sigma (+L_m)$ forces the current in the corresponding diode
    - $L_m$ commutates current between windings
Comparison: 1 IGBT with $f = 7$ kHz and 3 IGBTs with $f = 33$ kHz

$U_{DC} = 600$ V
$I_L = 12$ A
Inductance for Magnetic Free Wheeling

- Common core design
- Separate core design

Simpler, but bigger size (not yet explored completely)
Bridge Branch with 5 Semiconductor Modules in Parallel
Measurement of Diode Current and Diode Voltage (operation with 5 paralleled IGBT/diode modules)

\[ U_{DC} = 560 \text{ V} \]
\[ I_L = 20 \text{ A}_{\text{peak}} \]

Sequential currents in phases L1 of 5 paralleled inverters
Outline

- Introduction (Virtual Machine)
- Power Stage for High Switching Frequencies
  - Principle of Sequential/Interleaved Switching
  - Principle of Magnetic Freewheeling Control
  - Experimental Results
- Control of Virtual Machine
  - Problems with Standard PI Control
  - Possible Solutions
  - Successful “Machine Model”
- Summary

- Introduction (Virtual Grid)
- Power Stage for High Power and High Switching Frequencies
  - Connecting Inverters with different characteristics
- Control of Virtual Grid
  - Synchronous rotating frame (SRF) multi-loop PI controller
  - Stationary frame Proportional resonant (P+R) controller
  - Linear quadratic (LQR) optimal state space controller
- Experimental Results
- Summary
Phase Current, IGBT Current and Diode Current
(3-phase operation with 5 semiconductors in parallel)

U_{DC} = 560 \text{ V}
I_{L} = 20 \text{ A peak}
t_{ms}
Outline

- Introduction (Virtual Machine)
- Power Stage for High Switching Frequencies
  - Principle of Sequential/Interleaved Switching
  - Principle of Magnetic Freewheeling Control
  - Experimental Results
- Control of Virtual Machine
  - Problems with Standard PI Control
  - Possible Solutions
  - Successful “Machine Model”
- Summary

- Introduction (Virtual Grid)
- Power Stage for High Power and High Switching Frequencies
  - Connecting Inverters with different characteristics
- Control of Virtual Grid
  - Synchronous rotating frame (SRF) multi-loop PI controller
  - Stationary frame Proportional resonant (P+R) controller
  - Linear quadratic (LQR) optimal state space controller
- Experimental Results
- Summary
Outline

- Introduction (Virtual Machine)
- Power Stage for High Switching Frequencies
  - Principle of Sequential/Interleaved Switching
  - Principle of Magnetic Freewheeling Control
  - Experimental Results
- Control of Virtual Machine
  - Problems with Standard PI Control
  - Possible Solutions
  - Successful “Machine Model”
- Summary

- Introduction (Virtual Grid)
- Power Stage for High Power and High Switching Frequencies
  - Connecting Inverters with different characteristics
- Control of Virtual Grid
  - Synchronous rotating frame (SRF) multi-loop PI controller
  - Stationary frame Proportional resonant (P+R) controller
  - Linear quadratic (LQR) optimal state space controller
- Experimental Results
- Summary
Problems with Standard PI Control

\[ U_{DC1} \downarrow \quad \text{inverter under test} \]

\[ U_{DC2} \downarrow \]

\[ u_s \quad i_s \]

\[ i_s^* \]

\[ \text{machine model} \]

\[ \text{PWM} \]

\[ 2 \quad 3 \]

\[ 6 \]
Problems with Standard PI Control

inverter under test

machine model

PWM
Problems with PI Control

• Basic Idea :
  the current control of the „Virtual Machine“
  is *significantly faster* than the control of the inverter under test

→ the control of the inverter under test
  *cannot react* on the „enforced“ current

• Facts :
  a PI controller is – at least with respect to its I component – *not fast!* (!)
→ the control of the inverter under test
  „*is fighting*“ against the control of the „Virtual Machine“
Outline

- Introduction (Virtual Machine)
- Power Stage for High Switching Frequencies
  - Principle of Sequential/Interleaved Switching
  - Principle of Magnetic Freewheeling Control
  - Experimental Results
- Control of Virtual Machine
  - Problems with Standard PI Control
  - Possible Solutions
  - Successful “Machine Model”
- Summary

- Introduction (Virtual Grid)
- Power Stage for High Power and High Switching Frequencies
  - Connecting Inverters with different characteristics
- Control of Virtual Grid
  - Synchronous rotating frame (SRF) multi-loop PI controller
  - Stationary frame Proportional resonant (P+R) controller
  - Linear quadratic (LQR) optimal state space controller
- Experimental Results
- Summary
T-Filter Between Inverters Instead of Inductance:

inverter under test

$U_{DC1}$

$U_{DC2}$

PWM

machine model

$i_s^*$
Proposals

• **T-Filter Between Inverters Instead of Inductance:**

  → the current of „Virtual Machine“ is allowed to be **different** to the current of the inverter under test

  → the control of the inverter under test does not „fight“ against the control of „Virtual Machine“

• **Disadvantages**

  → T-Filter is **more complex** than an inductance with parallel windings

  → the current of „Virtual Machine“ is **not identical** to the current of the inverter under test
Proposals

• State Control Instead of PI Control

→ was proposed by the University of South Carolina (collaboration project with Schindler)
→ the state control of „Virtual Machine“ „overrules“ the control of the inverter under test

• Disadvantages

→ optimisation/adjustment of state controllers is more complex than optimisation of PI controllers
→ proposal is not suitable for small and medium sized enterprises
Outline

- Introduction (Virtual Machine)
- Power Stage for High Switching Frequencies
  - Principle of Sequential/Interleaved Switching
  - Principle of Magnetic Freewheeling Control
  - Experimental Results
- Control of Virtual Machine
  - Problems with Standard PI Control
  - Possible Solutions
  - Successful “Machine Model”
- Summary

- Introduction (Virtual Grid)
- Power Stage for High Power and High Switching Frequencies
  - Connecting Inverters with different characteristics
- Control of Virtual Grid
  - Synchronous rotating frame (SRF) multi-loop PI controller
  - Stationary frame Proportional resonant (P+R) controller
  - Linear quadratic (LQR) optimal state space controller
- Experimental Results
- Summary
Proposals

• Inverted Machine Model

⇒ in replacement of a model
  calculating machine currents as a reaction on terminal voltages

⇒ a model is applied
  calculating induced machine voltages as a reaction on „enforced“ machine currents
Inverted Machine Model

input: current

output: induced voltage
output: rotor speed

rotor winding

mechanical system
original idea
final idea
Proposals

• Inverted Machine Model

→ in replacement of a model
calculating machine currents as a reaction on terminal voltages

→ a model is applied
calculating induced machine voltages as a reaction on „enforced“ machine currents

• Advantages

→ current controllers do not „fight“ against each other
→ voltage sensors are not necessary at the output of the inverter under test !!!
Measurements

phase current

speed

speed reversal
Measurements

phase current

speed

speed reversal
Measurements

acceleration from standstill to rated speed at no load

speed

quadrature current
Measurements

fast acceleration from standstill to rated speed at no load

stator voltage $u_\alpha$

rotor flux $\Phi_\alpha$

stator currents $i_a, i_b$
Measurements

slow acceleration from standstill to rated speed at no load

- stator current(s)
- stator voltage
- rotor flux
- speed
Operation of the Machine Model

input current, rotor flux, induced voltage at rated speed and low load
Measurements

phase current

speed

“virtual” load step

TUM

IEEE POWER ELECTRONICS SOCIETY
Powering a Sustainable Future
Measurements

“virtual” load step from 0% to 75% rated load at rated speed

speed
quadrature current
Outline

- Introduction (Virtual Machine)
- Power Stage for High Switching Frequencies
  - Principle of Sequential/Interleaved Switching
  - Principle of Magnetic Freewheeling Control
  - Experimental Results
- Control of Virtual Machine
  - Problems with Standard PI Control
  - Possible Solutions
  - Successful “Machine Model”
- Summary

- Introduction (Virtual Grid)
- Power Stage for High Power and High Switching Frequencies
  - Connecting Inverters with different characteristics
- Control of Virtual Grid
  - Synchronous rotating frame (SRF) multi-loop PI controller
  - Stationary frame Proportional resonant (P+R) controller
  - Linear quadratic (LQR) optimal state space controller
- Experimental Results
- Summary
Summary

• **interleaved switching** is a basis to design power stages with higher performances than usual

• **magnetic freewheeling control** enables **interleaved switching** even in the **diodes**

• **inverted machine model** avoids conflicts between current controllers ... and provides a scheme **without voltage sensors**

• inverter under test can be operated **in the same way** as with a **real AC machine**
Outline

- Introduction (Virtual Machine)
  - Power Stage for High Switching Frequencies
    - Principle of Sequential/Interleaved Switching
    - Principle of Magnetic Freewheeling Control
    - Experimental Results
  - Control of Virtual Machine
    - Problems with Standard PI Control
    - Possible Solutions
    - Successful “Machine Model”
  - Summary

- Introduction (Virtual Grid)
  - Power Stage for High Power and High Switching Frequencies
    - Connecting Inverters with different characteristics
  - Control of Virtual Grid
    - Synchronous rotating frame (SRF) multi-loop PI controller
    - Stationary frame Proportional resonant (P+R) controller
    - Linear quadratic (LQR) optimal state space controller
  - Experimental Results
  - Summary
Outline

- Introduction (Virtual Machine)
  - Power Stage for High Switching Frequencies
    - Principle of Sequential/Interleaved Switching
    - Principle of Magnetic Freewheeling Control
    - Experimental Results
  - Control of Virtual Machine
    - Problems with Standard PI Control
    - Possible Solutions
    - Successful “Machine Model”
  - Summary

- Introduction (Virtual Grid)
  - Power Stage for High Power and High Switching Frequencies
    - Connecting Inverters with different characteristics
  - Control of Virtual Grid
    - Synchronous rotating frame (SRF) multi-loop PI controller
    - Stationary frame Proportional resonant (P+R) controller
    - Linear quadratic (LQR) optimal state space controller
  - Experimental Results
  - Summary
Motivation and introduction

- Two Desired Characteristics of Modern Power Electronics System (PES)
  - High power processing capability.
    - High power, high voltage converter system etc.
  - High dynamic response ability.
    - Switching mode supply, high speed and precise servo motor drives etc.

- Most industry applications require only one Characteristic. Either *Power* or *Dynamic*!
Motivation and introduction

- Excessive requirements of a converter based PHiL system
  - High power rating
  - Large bandwidth
  
  *Examples*: Large Motor and Grid PHiL emulator

- Traditional PES topology with single type device *(Unsatisfactory!)*
  - ‘Inverter Cumulation’ extends the power and dynamic performance of a power electronic system
Motivation and introduction

- Explanation of ‘Inverter Cumulation’
  - Interconnection (parallel, series and cascade) of identical or different voltage source inverters via magnetic or galvanic coupling.

- Two investigated inverter cumulation topologies
  - Magnetic-parallel coupling of identical inverters.
    - Virtual machine
  - Magnetic-series coupling of different inverters.
    - Virtual grid
Magnetic-series coupling of different inverters

Introduction

• Grid emulator: reproduce typical grid faults for grid-connected system.

• State of art:
  – Linear amplifier-based (expensive)
  – Transformer-based (bulky, low dynamic)
  – Generator-based (expensive, bulky, complicate)

• Converter based GE
  – cost effective
  – compact, flexible
Magnetic-series coupling of different inverters

- Schematic of PHiL GE
  - Power source
  - PES
  - Controller with grid model
  - Sensors (V,I)

PES is controlled by RT system to emulate behaviors of grid.
Magnetic-series coupling of different inverters

- Typical faults of grid

1. Under voltage
2. Voltage dip
3. Frequency variation
4. 5\textsuperscript{th} voltage harmonic
5. Spikes and noises (23\textsuperscript{rd} voltage harmonic)
Outline

- Introduction (Virtual Machine)
- Power Stage for High Switching Frequencies
  - Principle of Sequential/Interleaved Switching
  - Principle of Magnetic Freewheeling Control
  - Experimental Results
- Control of Virtual Machine
  - Problems with Standard PI Control
  - Possible Solutions
  - Successful “Machine Model”
- Summary

- Introduction (Virtual Grid)
- Power Stage for High Power and High Switching Frequencies
  - Connecting Inverters with different characteristics
- Control of Virtual Grid
  - Synchronous rotating frame (SRF) multi-loop PI controller
  - Stationary frame Proportional resonant (P+R) controller
  - Linear quadratic (LQR) optimal state space controller
- Experimental Results
- Summary
Magnetic-series coupling of different inverters

- **Requirements of PES of GE**
  - High power fundamental waves
  - Low amplitude high order harmonics

- **Difficulties for the PES**
  - High power rating capability
  - High dynamic performance
  - Simultaneous power and dynamic requirements is difficult for traditional PES.
Magnetic-series coupling of different inverters

- Principle of ‘inverter cumulation’
  The required wave is split into:
  - High power low frequency component
  - High dynamic low amplitude component
- Different inverter cumulation
  - IGBT inverter
  - MOSFET inverter
Outline

- Introduction (Virtual Machine)
  - Power Stage for High Switching Frequencies
    - Principle of Sequential/Interleaved Switching
    - Principle of Magnetic Freewheeling Control
    - Experimental Results
  - Control of Virtual Machine
    - Problems with Standard PI Control
    - Possible Solutions
    - Successful “Machine Model”
- Summary

- Introduction (Virtual Grid)
  - Power Stage for High Power and High Switching Frequencies
    - Connecting Inverters with different characteristics
  - Control of Virtual Grid
    - Synchronous rotating frame (SRF) multi-loop PI controller
    - Stationary frame Proportional resonant (P+R) controller
    - Linear quadratic (LQR) optimal state space controller
- Experimental Results
- Summary
Magnetic-series coupling of different inverters

- Original topology series magnetic-coupling inverters

- Original idea from DVR, series AF
- Two inverters with total different parameters
- Via coupling inductor magnetically connected in series

<table>
<thead>
<tr>
<th></th>
<th>IGBT Inverter 1</th>
<th>MOSFET Inverter 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_{dc}$ [V]</td>
<td>580</td>
<td>50</td>
</tr>
<tr>
<td>$f_s$ [kHz]</td>
<td>8</td>
<td>50</td>
</tr>
<tr>
<td>$f_1$ [Hz]</td>
<td>50</td>
<td>1250</td>
</tr>
<tr>
<td>$V_{ph,\text{max}}$ [V]</td>
<td>110</td>
<td>25</td>
</tr>
</tbody>
</table>
Magnetic-series coupling of different inverters

- First attempt and failure
  - VSI with PWM:
    - Massive switching component
    - High distortion output
  - Output filter required
    - Sinusoidal waves
  - Idea is straightforward
  - Does not work!
Magnetic-series coupling of different inverters

- Charging mode of the MOSFET inverter
  - High amplitude pulses reflected by coupling inductor charge up the dc-link out of limitation
Magnetic-series coupling of different inverters

- Solution of the failure
  - Output filter should be added **before** the coupling inductor.

Final Topology
Outline

- Introduction (Virtual Machine)
- Power Stage for High Switching Frequencies
  - Principle of Sequential/Interleaved Switching
  - Principle of Magnetic Freewheeling Control
  - Experimental Results
- Control of Virtual Machine
  - Problems with Standard PI Control
  - Possible Solutions
  - Successful “Machine Model”
- Summary

- Introduction (Virtual Grid)
- Power Stage for High Power and High Switching Frequencies
  - Connecting Inverters with different characteristics
- Control of Virtual Grid
  - Synchronous rotating frame (SRF) multi-loop PI controller
  - Stationary frame Proportional resonant (P+R) controller
  - Linear quadratic (LQR) optimal state space controller
- Experimental Results
- Summary
Magnetic-series coupling of different inverters

- Basic element and control algorithm
  - Voltage source inverter with LC output filter

\[ i_{C_f} = C_f \frac{dV_{C_f}}{dt}, \]
\[ V_{L_f} = L_f \frac{di_{inv}}{dt}, \]
\[ V_{L_f} = V_{inv} - V_{C_f}, \]
\[ i_{C_f} = i_{inv} - i_{load}. \]
Magnetic-series coupling of different inverters

Control algorithm
- Control plant: LC filter
- Control target: LC filter output voltage
- Three investigated algorithms:
  - Synchronous rotating frame (SRF) multi-loop PI controller
  - Stationary frame Proportional resonant (P+R) controller
  - Linear quadratic (LQR) optimal state space controller
Outline

- Introduction (Virtual Machine)
- Power Stage for High Switching Frequencies
  - Principle of Sequential/Interleaved Switching
  - Principle of Magnetic Freewheeling Control
  - Experimental Results
- Control of Virtual Machine
  - Problems with Standard PI Control
  - Possible Solutions
  - Successful “Machine Model”
- Summary

- Introduction (Virtual Grid)
- Power Stage for High Power and High Switching Frequencies
  - Connecting Inverters with different characteristics
- Control of Virtual Grid
  - Synchronous rotating frame (SRF) multi-loop PI controller
  - Stationary frame Proportional resonant (P+R) controller
  - Linear quadratic (LQR) optimal state space controller
- Experimental Results
- Summary
Magnetic-series coupling of different inverters

- Synchronous rotating frame (SRF) multi-loop PI controller
  - All system variables transformed to the synchronous frame.
    - Complex calculation
    - Cross coupling

LC plant block diagram
Magnetic-series coupling of different inverters

- Synchronous rotating frame (SRF) multi-loop PI controller
  - Outer capacitor voltage PI controller cascaded with inner inverter current PI controller

![Controller block diagram]

- Decoupling network
Magnetic-series coupling of different inverters

- Synchronous rotating frame (SRF) multi-loop PI controller
  - Three assumptions for the controller optimization
    - After decoupling, two axis totally independent
    - Inverter can be view as an unit element in current loop
    - Inner loop can be view as an unit element in voltage loop

Two control loops with same structure!
Magnetic-series coupling of different inverters

- Synchronous rotating frame (SRF) multi-loop PI controller
  - Current loop controller optimization \((t_{set}, \sigma_{\%})\)

\[
F_{ic} = \frac{\omega_n^2}{s^2 + 2\xi\omega_ns + \omega_n^2} + \frac{s}{z} \frac{\omega_n^2}{s^2 + 2\xi\omega_ns + \omega_n^2}
\]

**Dominatio** \text{Addition '0'}

with \(\omega_n = \sqrt{\frac{k_{ii}}{L_f}}\), \(\xi = \frac{k_{pi}}{2\sqrt{k_{ii}L_f}}\), \(z = \frac{k_{ii}}{k_{pi}} = \frac{\omega_n}{2\xi}\).

**Domination:** 2\(^{nd}\) order system

**Amplitude Optimum**

\[
\omega_n = \sqrt{\frac{k_{ii}}{L_f}} = \frac{3}{t_{set}} \Rightarrow k_{ii} = \frac{9L_f}{t_{set}^2}
\]

\[
\xi = \frac{k_{pi}}{2\sqrt{k_{ii}L_f}} \approx 0.707 \Rightarrow k_{pi} = 2\xi \sqrt{k_{ii}L_f}
\]
Magnetic-series coupling of different inverters

- Synchronous rotating frame (SRF) multi-loop PI controller
  - Current loop controller optimization \( t_{\text{set}}, \sigma^{0\%} \)

\[
F_{ic} = \frac{\omega_n^2}{s^2 + 2\xi\omega_ns + \omega_n^2} + \frac{s}{z} \frac{\omega_n^2}{s^2 + 2\xi\omega_ns + \omega_n^2}
\]

**Dominatio** + **Addition ‘0’**

with \( \omega_n = \sqrt{\frac{k_{ii}}{L_f}} \), \( \xi = \frac{k_{pi}}{2\sqrt{k_{ii}L_f}} \), \( z = \frac{k_{ii}}{k_{pi}} = \frac{\omega_n}{2\xi} \).

Addition ‘0’ cause oscillation:
Increase damping ration to 2
Magnetic-series coupling of different inverters

- Synchronous rotating frame (SRF) multi-loop PI controller
  - voltage loop controller optimization \( t_{set} \)
    - Same tuning process
    - With much slower setting time \( t_{set} \) to avoid influence from current loop
Magnetic-series coupling of different inverters

- Synchronous rotating frame (SRF) multi-loop PI controller
  - Summary
    - Easy to understand and simple to implement
    - Complex coordinate transformation
    - Difficult to optimize
    - Sensitive to frequency variation
Outline

- Introduction (Virtual Machine)
- Power Stage for High Switching Frequencies
  - Principle of Sequential/Interleaved Switching
  - Principle of Magnetic Freewheeling Control
  - Experimental Results
- Control of Virtual Machine
  - Problems with Standard PI Control
  - Possible Solutions
  - Successful “Machine Model”
- Summary

- Introduction (Virtual Grid)
- Power Stage for High Power and High Switching Frequencies
  - Connecting Inverters with different characteristics
- Control of Virtual Grid
  - Synchronous rotating frame (SRF) multi-loop PI controller
  - Stationary frame Proportional resonant (P+R) controller
  - Linear quadratic (LQR) optimal state space controller
- Experimental Results
- Summary
Magnetic-series coupling of different inverters

- Stationary frame Proportional resonant (P+R) controller
  - All controller implemented in $\alpha\beta$ frame.
    - No coordinate transformation
    - No cross-coupling item
  - Both positive and negative sequence control

$$G_{PR}^{\alpha\beta}(s) = \begin{bmatrix} k_p + \frac{k_i s}{s^2 + \omega_{res}^2} & 0 \\ 0 & k_p + \frac{k_i s}{s^2 + \omega_{res}^2} \end{bmatrix}$$
Magnetic-series coupling of different inverters

- Stationary frame Proportional resonant (P+R) controller
  - Basic principle:
    - equivalent transformation of synchronous PI controller in stationary frame

\[
G_{DC}^{dq+}(s) = \begin{bmatrix}
  k_p + \frac{k_i}{s} & 0 \\
  0 & k_p + \frac{k_i}{s}
\end{bmatrix} \Rightarrow G_{AC}^{\alpha\beta}(s)^+ = \begin{bmatrix}
  k_p + \frac{k_i s}{s^2 + \omega_0^2} & -\frac{k_i \omega_{res}}{s^2 + \omega_{res}^2} \\
  \frac{k_i \omega_{res}}{s^2 + \omega_{res}^2} & k_p + \frac{k_i s}{s^2 + \omega_{res}^2}
\end{bmatrix}
\]

\[
G_{DC}^{dq-}(s) = \begin{bmatrix}
  k_p + \frac{k_i}{s} & 0 \\
  0 & k_p + \frac{k_i}{s}
\end{bmatrix} \Rightarrow G_{AC}^{\alpha\beta}(s)^- = \begin{bmatrix}
  k_p + \frac{k_i s}{s^2 + \omega_0^2} & \frac{k_i \omega_{res}}{s^2 + \omega_{res}^2} \\
  -\frac{k_i \omega_{res}}{s^2 + \omega_{res}^2} & k_p + \frac{k_i s}{s^2 + \omega_{res}^2}
\end{bmatrix}
\]
Magnetic-series coupling of different inverters

- **Stationary frame Proportional resonant (P+R) controller**
  - Basic principle:
    - equivalent transformation of synchronous PI controller in stationary frame

\[
G^\alpha_\beta_{PR}(s) = \begin{bmatrix}
k_p + \frac{k_i s}{s^2 + \omega_{res}^2} & 0 \\
0 & k_p + \frac{k_i s}{s^2 + \omega_{res}^2}
\end{bmatrix}
\]

infinite gain at the resonant frequency \( \omega_{res} \)
Magnetic-series coupling of different inverters

- Stationary frame Proportional resonant (P+R) controller
  - Problem of the ideal PR controller
    - Ideal lossless filter difficult or impossible to implement
    - Sensitive to the frequency variation
  - Practical PR controller
    - Adding cut-off frequency $\omega_c$

$$G_{PR}^{\alpha\beta}(s) = \begin{bmatrix} k_p + \frac{2k_i\omega_cs}{s^2 + 2\omega_cs + \omega_{res}^2} & 0 \\ 0 & k_p + \frac{2k_i\omega_cs}{s^2 + 2\omega_cs + \omega_{res}^2} \end{bmatrix}$$
Magnetic-series coupling of different inverters

- Stationary frame Proportional resonant (P+R) controller
  - Practical PR controller
    - Widen bandwidth around $\omega_{\text{res}}$
    - Better harmonic rejection
Magnetic-series coupling of different inverters

- Stationary frame Proportional resonant (P+R) controller
  - Block diagram of the PR controller of the grid emulator ($\alpha$-axis)
    - Capacitor voltage $P+R$ controller
    - inverter current inner $P$ controller
Magnetic-series coupling of different inverters

- Stationary frame Proportional resonant (P+R) controller
  - Summary
    - Less calculation effort
    - Wider control bandwidth
    - Better harmonic rejection
    - Difficult to optimized
Outline

- Introduction (Virtual Machine)
  - Power Stage for High Switching Frequencies
    - Principle of Sequential/Interleaved Switching
    - Principle of Magnetic Freewheeling Control
    - Experimental Results

- Control of Virtual Machine
  - Problems with Standard PI Control
  - Possible Solutions
  - Successful “Machine Model”

- Summary

- Introduction (Virtual Grid)
  - Power Stage for High Power and High Switching Frequencies
    - Connecting Inverters with different characteristics

- Control of Virtual Grid
  - Synchronous rotating frame (SRF) multi-loop PI controller
  - Stationary frame Proportional resonant (P+R) controller
  - Linear quadratic (LQR) optimal state space controller

- Experimental Results

- Summary
Magnetic-series coupling of different inverters

- **Linear quadratic (LQR) optimal state space controller**
  - Controller in stationary frame
  - Instinct close-loop stability
  - Unique control law
  - Good interpretation of parameters optimization
Magnetic-series coupling of different inverters

- Linear quadratic (LQR) optimal state space controller
  - Basic principle of state space control
  The state space equation of a regulator system (no reference input)

\[
\dot{x} = Ax + Bu \\
\dot{x}(t) = (A - BK)x(t) \\
x(t) = e^{(A-BK)t}x(0) \\
u = -kx
\]

By properly choosing matrix \( k \), the eigenvalues of matrix \( A - BK \) in the left half \( s \) plane, System approaches 0 at steady state with controllable dynamic process. ---- Pole Placement
Magnetic-series coupling of different inverters

- Linear quadratic (LQR) optimal state space controller
  - For a system with time varying reference input

State space equation of VSI with LC filter is:

\[
\begin{align*}
\dot{x} &= Ax + Bu + Dd \\
y &= Cx \\
u &= -Kx + k_f \xi \\
\dot{\xi} &= r - y = r - Cx
\end{align*}
\]

where \( x = \begin{bmatrix} V_{C_f} \\ i_{inv} \end{bmatrix} \), \( u = V_{inv} \), \( y = V_{C_f} \), \( d = i_l \)

and \( A = \begin{bmatrix} 0 & \frac{1}{C_f} \\ -\frac{1}{L_f} & 0 \end{bmatrix} \), \( B = \begin{bmatrix} 0 \\ \frac{1}{L_f} \end{bmatrix} \), \( C = \begin{bmatrix} 1 & 0 \end{bmatrix} \), \( D = \begin{bmatrix} -\frac{1}{C_f} & 0 \end{bmatrix} \).
Magnetic-series coupling of different inverters

- **Linear quadratic (LQR) optimal state space controller**
  - The previous system can be reformed as error regulator as below:

  \[
  \begin{align*}
    \dot{e} &= \hat{A}e + \hat{B}u_e \\
    u_e &= -\hat{K}e
  \end{align*}
  \]

  By choosing a proper feedback matrix, the error states \(e(t)\) will approach to 0

  \[
  \hat{A} = \begin{bmatrix}
    0 & \frac{1}{C_f} & 0 \\
    -\frac{1}{L_f} & 0 & 0 \\
    -1 & 0 & 0
  \end{bmatrix}, \quad \hat{B} = \begin{bmatrix}
    0 \\
    \frac{1}{L_f} \\
    0
  \end{bmatrix}
  \]

  \[
  \hat{K} = \begin{bmatrix}
    K_v & K_i & -k_I
  \end{bmatrix}
  \]
Magnetic-series coupling of different inverters

- **Linear quadratic (LQR) optimal state space controller**
  - Problem of pole placement
    - Relies on designer’s experiences
    - dynamic and control energy are mutual constraints
    - Very hard to be optimal
  - LQR
    - It determines the optimal matrix by minimizing cost function

\[
J = \int_0^\infty (e^T Q e + u_e^T R u_e) dt
\]
Magnetic-series coupling of different inverters

- **Linear quadratic (LQR) optimal state space controller**
  - $Q$ (real symmetric matrix) represents the weightiness of the state error vector away from final value 0.
  - $R$ (real symmetric matrix) represents the control effort of regulating the state error vector to 0.

\[
J = \int_{0}^{\infty} (e^T Q e + u_e^T R u_e) dt
\]
Magnetic-series coupling of different inverters

- **Linear quadratic (LQR) optimal state space controller**
  The derivation of the optimal matrix is out of the scope.
  
  **MATLAB command**
  
  \[
  \text{lqr}(\hat{A}, \hat{B}, Q, R).
  \]
  
  **Algebraic Riccati equation**
  
  \[
  \hat{A}^T P + P \hat{A} - P \hat{B} R^{-1} \hat{B}^T P + Q = 0
  \]
  
  \[
  \hat{K} = -R^{-1} \hat{B}^T P
  \]
  
  **Faster transient response**, large weighting factor of \( Q \)
  
  \[Q = \begin{bmatrix}
  1 & 0 & 0 \\
  0 & 1 & 0 \\
  0 & 0 & 200/C_f
  \end{bmatrix}, \quad R = 1\]
  
  \[
  \hat{A} = \begin{bmatrix}
  0 & \frac{1}{C_f} & 0 \\
  -\frac{1}{L_f} & 0 & 0 \\
  -1 & 0 & 0
  \end{bmatrix}, \quad \hat{B} = \begin{bmatrix}
  0 \\
  \frac{1}{L_f} \\
  0
  \end{bmatrix}
  \]
Magnetic-series coupling of different inverters

- Linear quadratic (LQR) optimal state space controller
  - Instinct stability
  - Optimized
  - Less variables required
  - Less design parameters
  - Good performance

- Difficult to understand
- Difficult to model the SS equations
Outline

- Introduction (Virtual Machine)
- Power Stage for High Switching Frequencies
  - Principle of Sequential/Interleaved Switching
  - Principle of Magnetic Freewheeling Control
  - Experimental Results
- Control of Virtual Machine
  - Problems with Standard PI Control
  - Possible Solutions
  - Successful “Machine Model”
- Summary

- Introduction (Virtual Grid)
- Power Stage for High Power and High Switching Frequencies
  - Connecting Inverters with different characteristics
- Control of Virtual Grid
  - Synchronous rotating frame (SRF) multi-loop PI controller
  - Stationary frame Proportional resonant (P+R) controller
  - Linear quadratic (LQR) optimal state space controller
- Experimental Results
- Summary
Experimental verification

- Technical standards of the grid emulation
  - EN 50160 voltage characteristics of public distribution system
  - IEEE 1547 interconnection distributed resources with electric power systems
  - IEC 61000-4-x transient immunity test
Experimental verification

- Technical standards of the grid emulation

<table>
<thead>
<tr>
<th>Item</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage variation</td>
<td>±1%U_n</td>
</tr>
<tr>
<td>Frequency variation</td>
<td>±0.1 Hz</td>
</tr>
<tr>
<td>Harmonics distortion</td>
<td>THD_v &lt; 2.5%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Order h</th>
<th>5</th>
<th>7</th>
<th>11</th>
<th>13</th>
<th>17</th>
<th>19</th>
<th>23</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative voltage (%)</td>
<td>6</td>
<td>5</td>
<td>3.5</td>
<td>3</td>
<td>2</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>
Experimental verification

Linear load with PI-controller
Nonlinear load with P+R-controller
Linear load with LQR controller
• Linear load with PI-controller
• Nonlinear load with P+R-controller
• THD analysis
  – Nonlinear load with PI and PR controller

 PR controller has a better THD due to its wider bandwidth.
• Linear load with LQR controller

(a) Sag Event wide view.

(b) Sag fault occurrence and clear zoom view.

(c) Trip Event wide view.

(d) Trip fault occurrence and clear zoom view.
- Low-order harmonics programmability

(a) Low order harmonics superposition.

(b) FFT spectrum and THD.

<table>
<thead>
<tr>
<th>Order $h$</th>
<th>1</th>
<th>5</th>
<th>7</th>
<th>11</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative Voltage (%)</td>
<td>100</td>
<td>6</td>
<td>5</td>
<td>3.5</td>
<td>...</td>
</tr>
</tbody>
</table>
• Fault-ride-through and frequency variation
• High frequency harmonics injection capability
• High frequency harmonics injection transient process
Outline

- Introduction (Virtual Machine)
- Power Stage for High Switching Frequencies
  - Principle of Sequential/Interleaved Switching
  - Principle of Magnetic Freewheeling Control
  - Experimental Results
- Control of Virtual Machine
  - Problems with Standard PI Control
  - Possible Solutions
  - Successful “Machine Model”
- Summary

- Introduction (Virtual Grid)
- Power Stage for High Power and High Switching Frequencies
  - Connecting Inverters with different characteristics
- Control of Virtual Grid
  - Synchronous rotating frame (SRF) multi-loop PI controller
  - Stationary frame Proportional resonant (P+R) controller
  - Linear quadratic (LQR) optimal state space controller
- Experimental Results
- Summary
Grid emulator limitation discussion

- limited current rating
  (saturation effect of magnetic component)
- bi-directional power flow possible
  with fully controlled rectifier
- no zero sequence emulation capability
  (only positive and negative sequence)
Outlook

- New cascade inverter cumulation topologies
Thank You !!!

Any Questions ?

Prof. Dr.-Ing. Ralph Kennel
Technische Universität München
Electrical Drive Systems and Power Electronics