EE 459/559: Control and Applications of Power Electronics

Lecture 5: Advanced Concepts in Control of Power Electronics

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Outline

- **HVDC Overview**
- **Real Time Simulation and Hardware in the Loop (HIL)**
- **Digital/Discrete Implementation of Controllers**

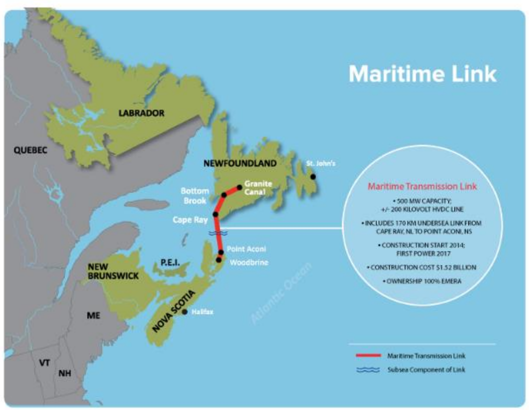
High Voltage DC Transmission

• $P = IV$ if power is fixed $\Rightarrow$ Increasing $V\uparrow$ $\Rightarrow$ reduce $I\downarrow$

Motivation

Voltage levels ≥ 100 kV

- For large power transmission, higher voltages reduce line losses: $P_{\text{line}} = I^2 R$ losses.
- Power transmission between two long distance areas
- A vast majority of renewables such as offshore wind farms are built long distances away from the consumers
- In general, power transfer between two or more zones → Multi terminal HVDC



Maritime Link - Canada

Offshore Windfarms

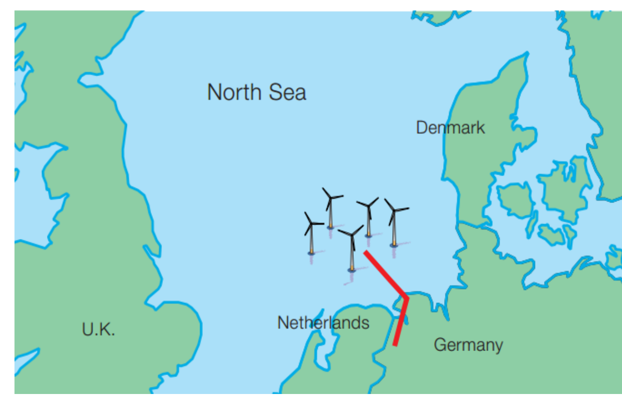


ABB Dolwin 1 – HVDC Light

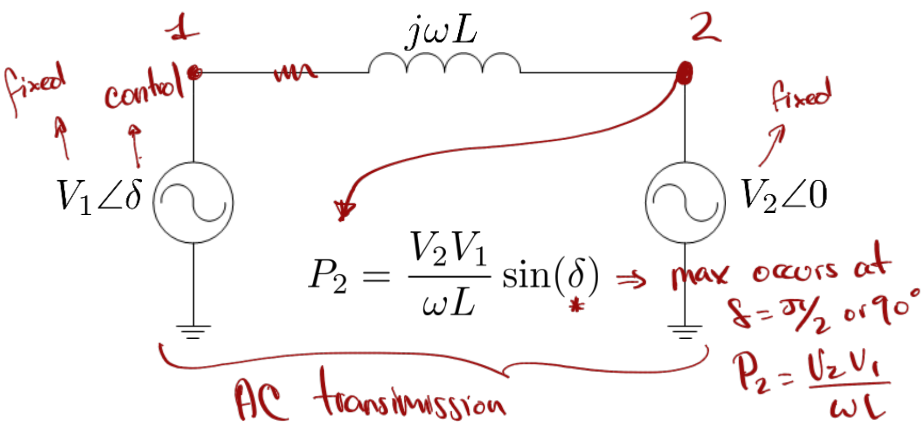
HVDC vs HVAC

AC Transmission

- For ac transmission, the maximum power transfer between two areas depends on the line inductance
- The losses are increased if we take into account the resistance of the ac line (larger than dc due to skin effect)

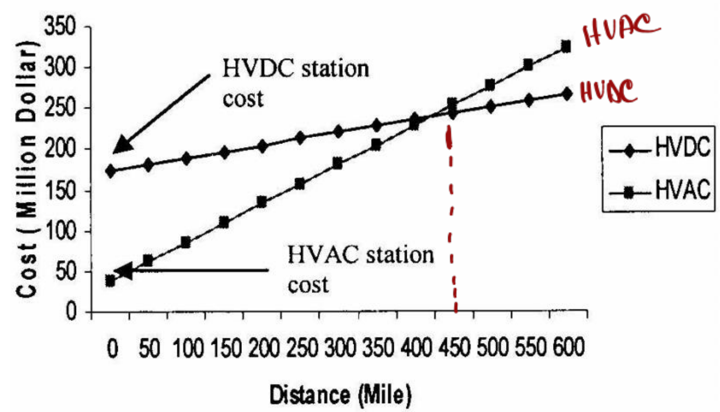
DC Transmission

- Does not depend on inductance for power flow, only resistance
- Resistance is lower than ac cables (due to skin effect.)
- *Need to take into account the cost of power converters



$$P_2 = \frac{V_2 V_1}{\omega L}\sin(\delta) \Rightarrow \text{max occurs at } \delta = \pi/2 \text{ or } 90^\circ$$

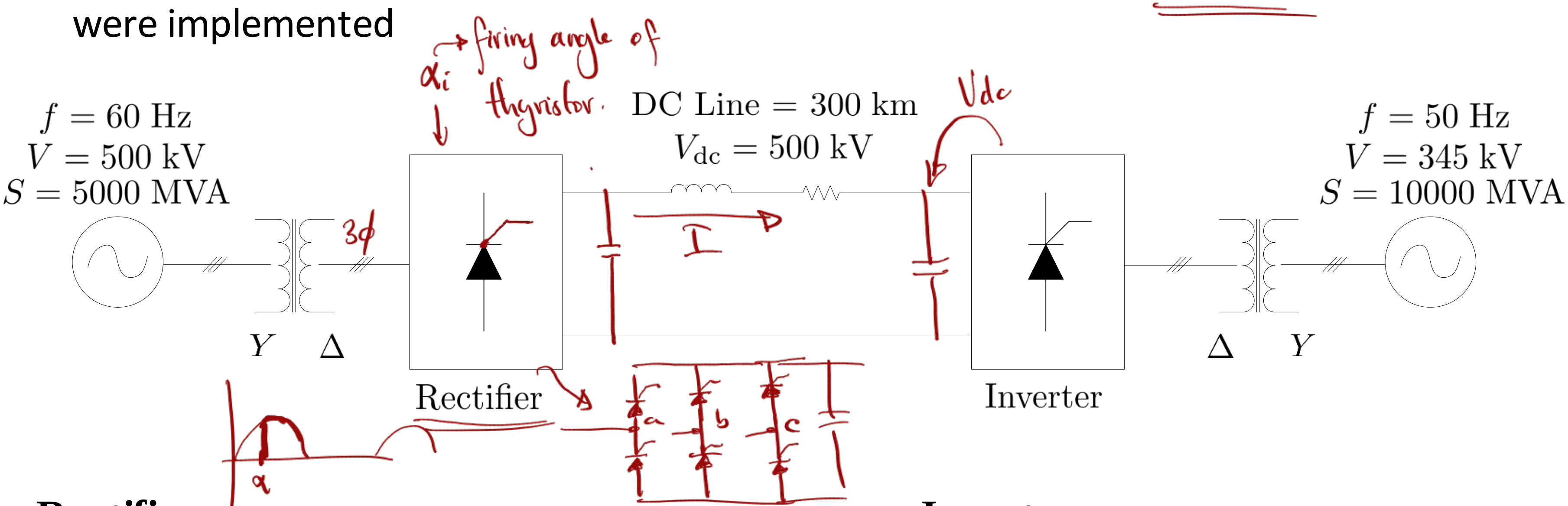
$$P_2 = \frac{V_2 V_1}{\omega L}$$



[1] K. Meah and S. Ula, "Comparative evaluation of HVDC and HVAC transmission systems," in *IEEE PES*, 2007

Point to Point HVDC (Past)

- HVDCs have generally been used for point to point power transmission
- Due to the high voltage stress on the power devices (> 400 kV), **thyristor** based HVDC were implemented



Rectifier

- Control the dc link current ~ Power transfer
- Control input: α_1 (firing angle)

Inverter

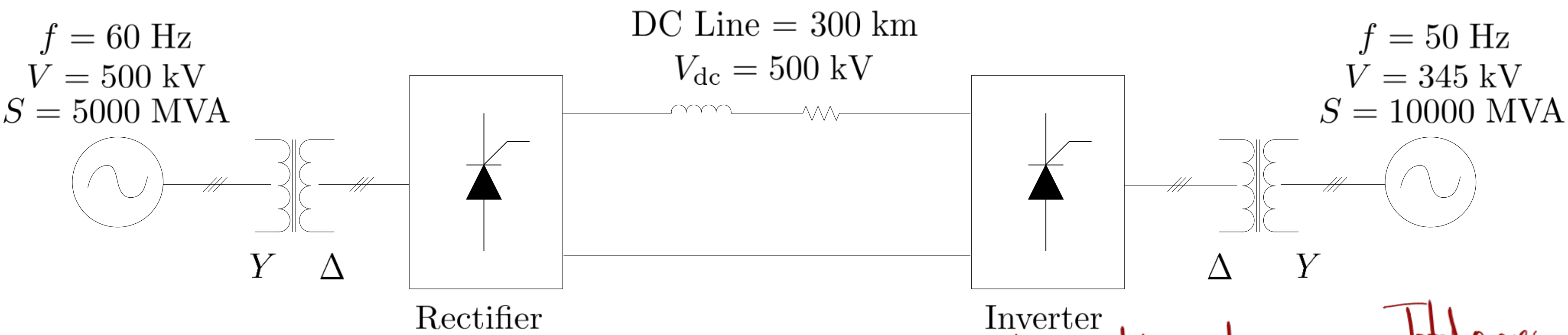
- Control the dc link Voltage (slack)
- Control input: α_2 (firing angle)

- **Only one control variable for a thyristor based converter**

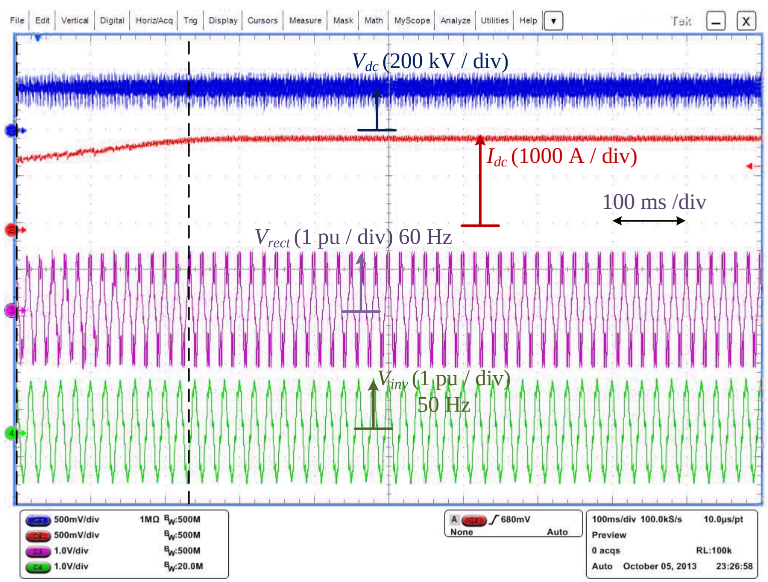
α_1

⇒ You can only track/regulate 1 variable

Point to Point Waveforms

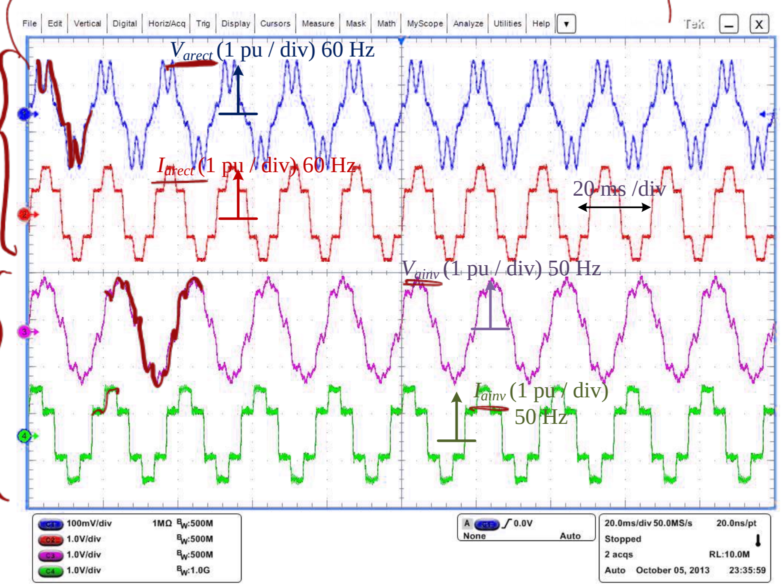


→ waveforms have a lot of harmonics ⇒ Total power factor is reduced



AC at Rect.

AC at Inverter



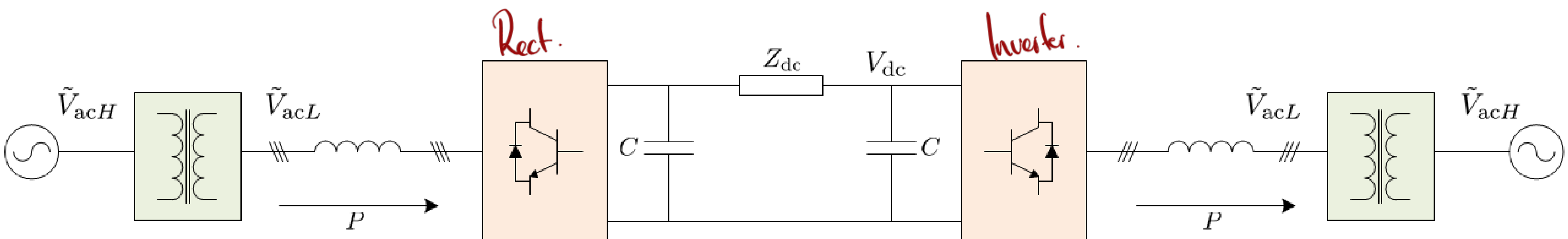
Drawbacks of Thyristor Based HVDC

Thyristor Based HVDC

- Large harmonic distortion at the ac sides – need ac filters (increases cost)
- We cannot control reactive power at the ac side (α_i)
  - Important for weak ac systems where the ac side voltage is not very stable

Solutions:

- **Voltage Source Converter (VSC) based HVDC**
- Control both active and reactive power



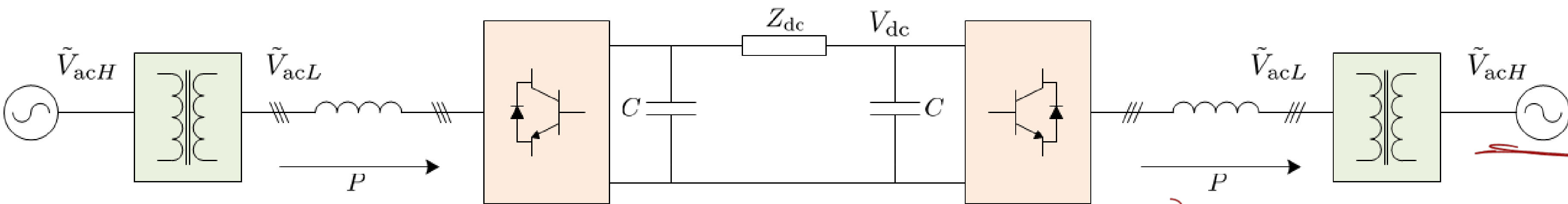
V_{dc}, Q

less harmonic distortion

$F_{sw} >> f$

P, Q

Voltage Source Converter (VSC) Based HVDC



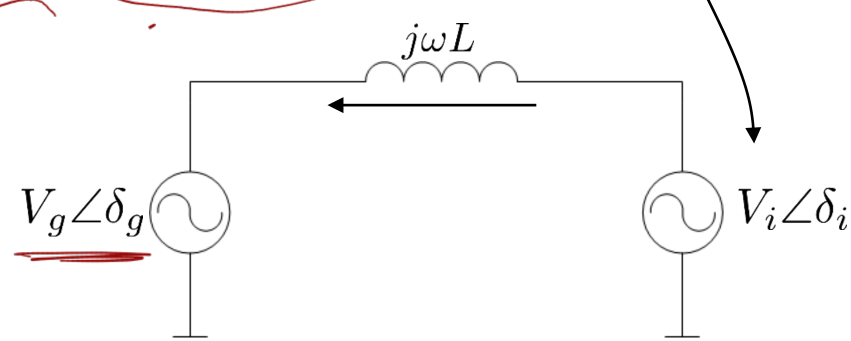
- In a typical VSC inverter, the active and reactive power can be controlled independently:

$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta) & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ -\sin(\theta) & -\sin(\theta - 2\pi/3) & -\sin(\theta + 2\pi/3) \\ \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

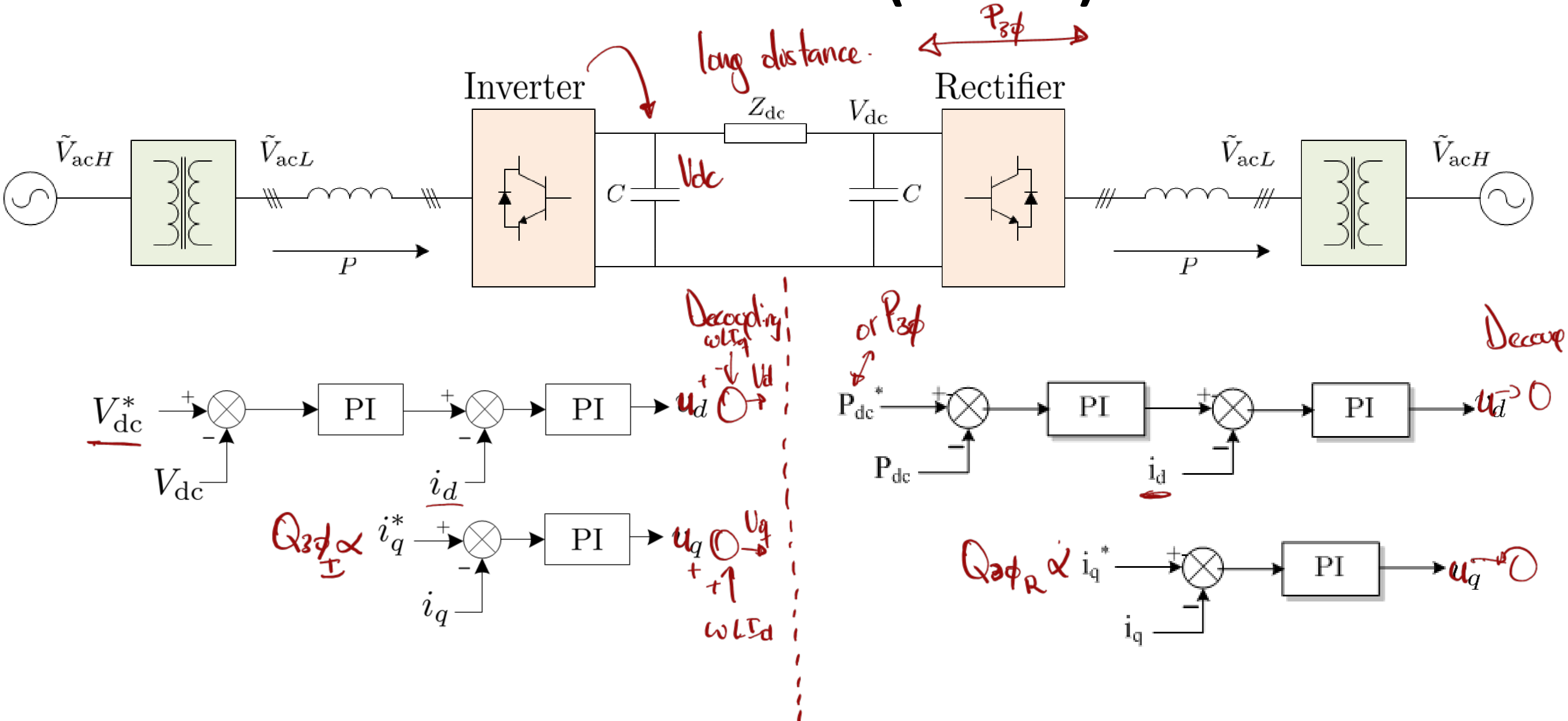
Control both V_i and δ_i!

$$P = V_d I_d + V_q I_q$$
$$Q = V_q I_d - V_d I_q$$
$$\Downarrow$$
$$P = V_d I_d$$
$$Q = -V_d I_q$$

if frame is aligned with V_d



VSC Based HVDC (Cont'd)

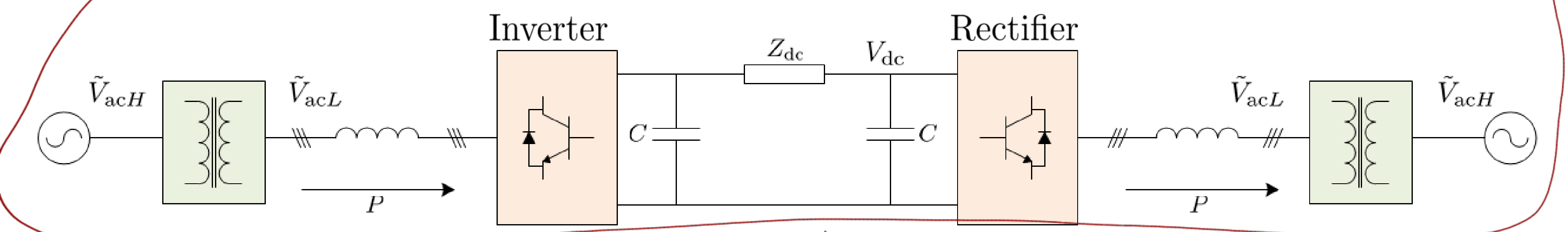


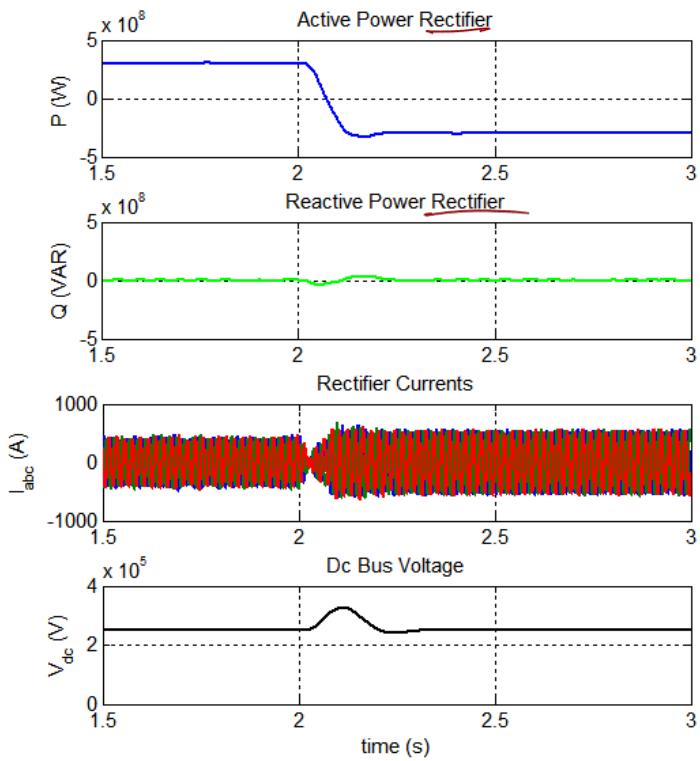
- Control of I_d implies control of active power:
  - I_d is used in the inverter to control V_{dc}
  - I_d is used in the rectifier to control the active power transmitted
- Control of I_q implies control of reactive power

$$P = V_d I_d$$

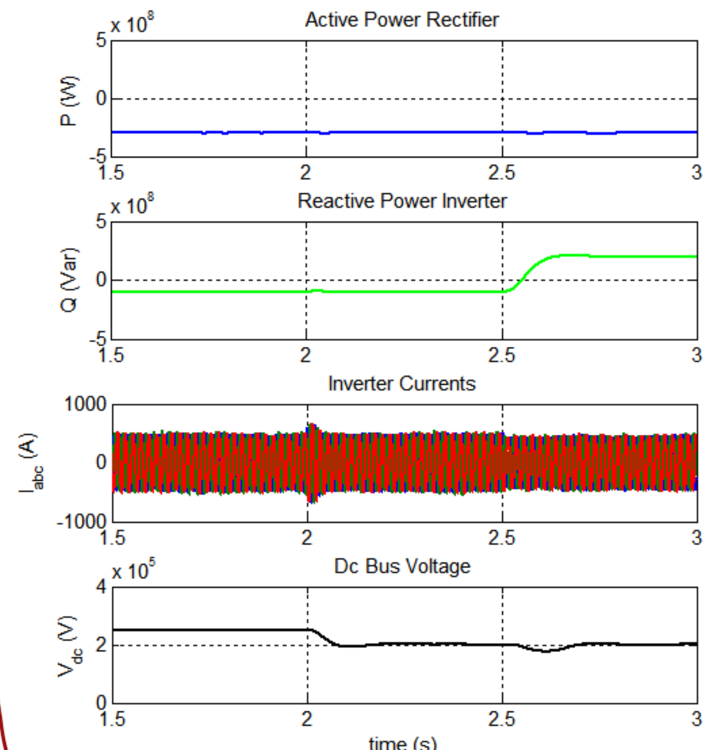
$$Q = -V_d I_q$$

Example VSC HVDC





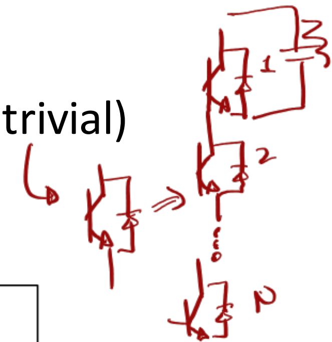
Case 1: Change in Active Power



Case 2: Change in Reactive Power and Dc Bus Voltage

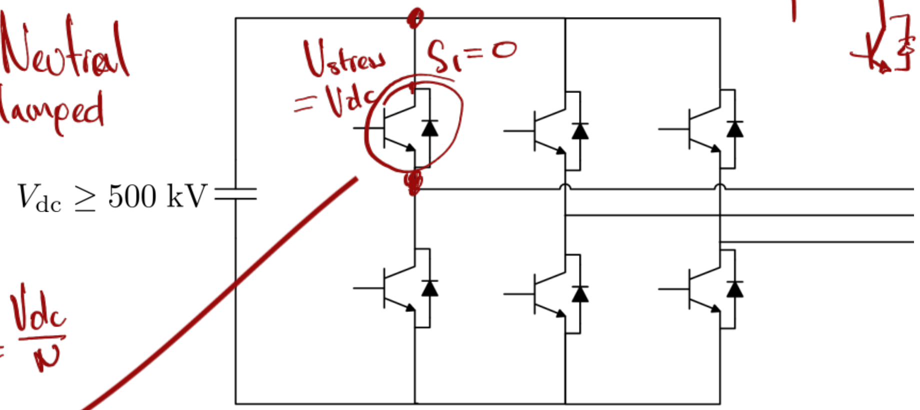
Challenges in VSC HVDC Implementation

- **Typical three level inverters**
  - Large voltage stress on the IGBTs - need to connect them in series (not trivial)
  - Large *dv/dt* implies large current distortion as well as EMI problems

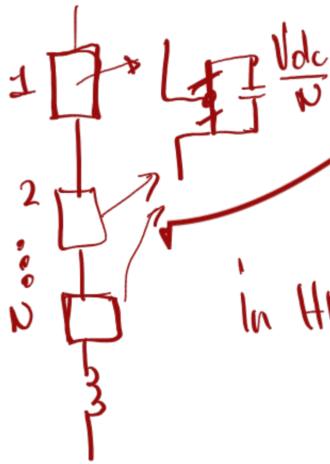


- **Solutions:**
  - Multilevel Converters
  - Modular Multilevel Converters

3-level Neutral Point Clamped



Arm



in HVDC $N \geq 100$ per arm ($\times 6 \times 2$)

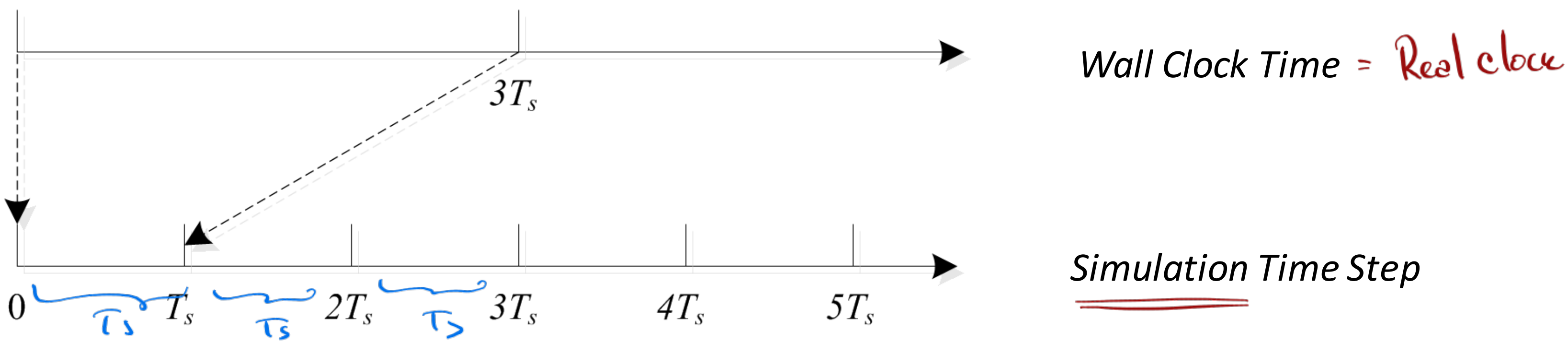
Outline

- **HVDC Overview**
- **Real Time Simulation and Hardware in the Loop (HIL)** Opal RT Typhoon HIL RTDS
- **Digital/Discrete Implementation of Controllers**

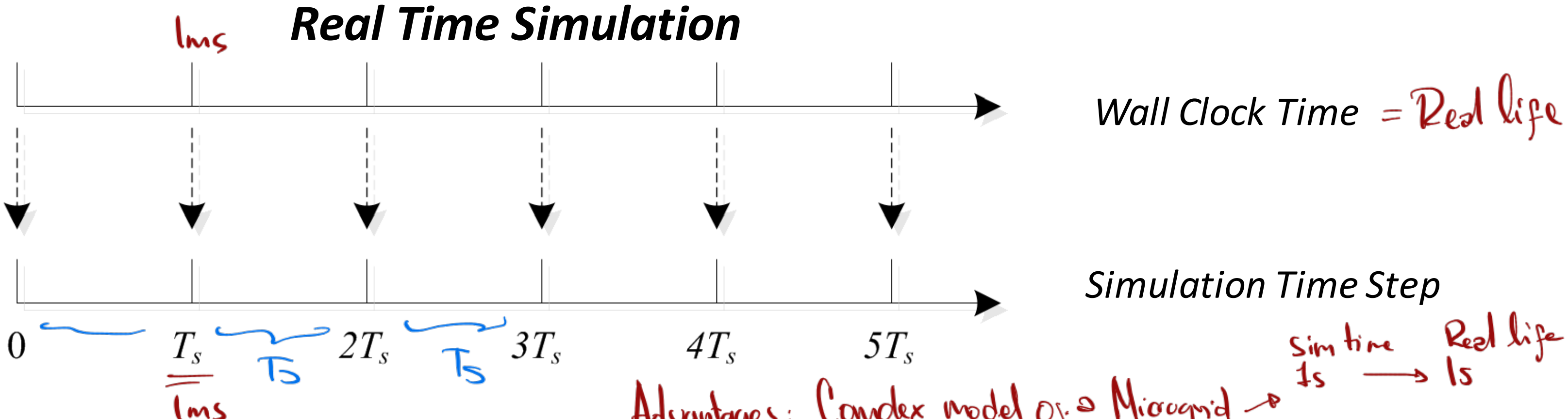
What is Real Time Simulation?

- Simulation of a model that executes at the same rate as an actual "wall clock" time. *How does it compare to offline simulation?*
- ***Example:***

Offline Simulation e.g. $T_s = 1ms$.



Real Time Simulation



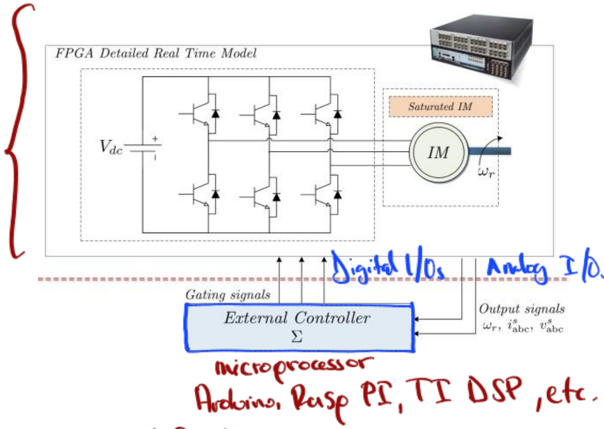
Advantages: Complex model of a Microgrid →
"Disadvantage" Powerful CPUs, FPGAs, GPU

Why Real Time?

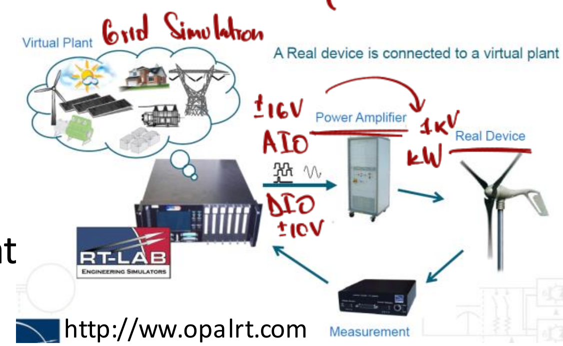
- **Why is real-time simulation important?**
  - Provide hardware-in-the-loop functions

- **Hardware-in-the-loop methodologies:**
  - **Control Hardware-in-the-Loop (CHIL)**
    - Validation of control strategies, e.g. electric machine drive speed / flux control

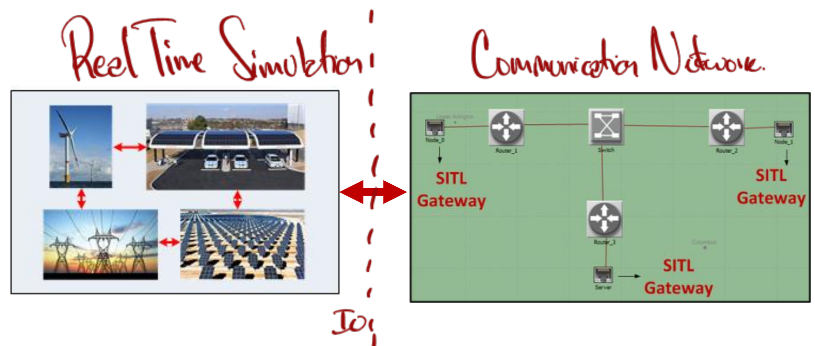
Real Time Simulation



  - **Power Hardware-in-the-Loop (PHIL)**
    - Validation of both electrical equipment and associat control strategies



  - **System-in-the-loop (SITL)**
    - Validation of communication strategies, e.g. cyber security

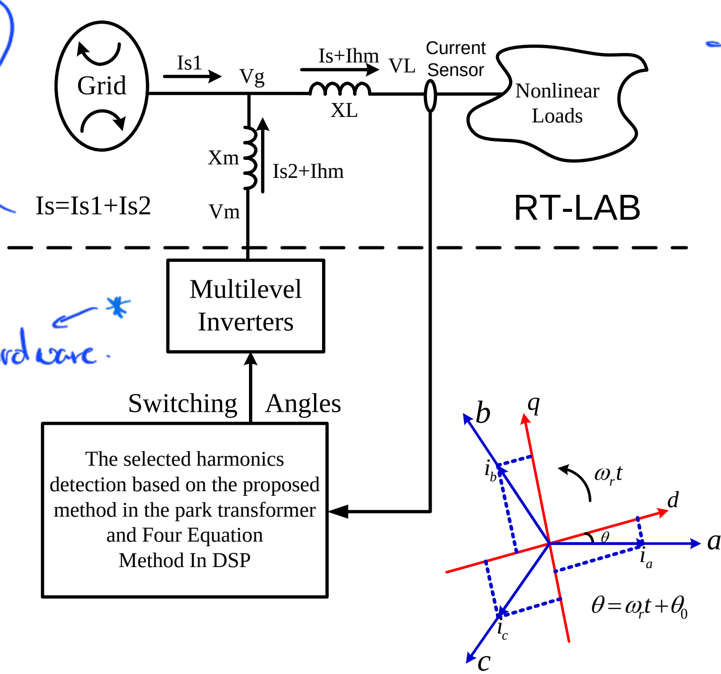


Applications

- *Renewable energy resources*
- *Smart grid / Microgrid*
- *Different types of land, sea, aerial vehicles*

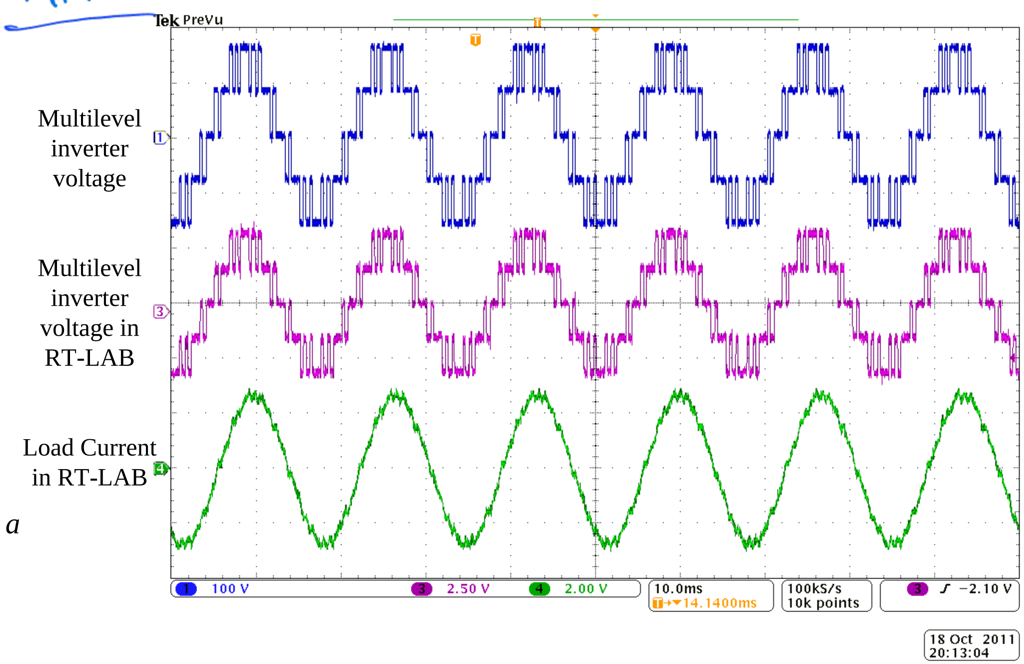
Example: Testing of control algorithms for multilevel inverters.

Real time Simulation



Hardware*

PHIL



Method 1: State Space Model

(Simpower Systems)

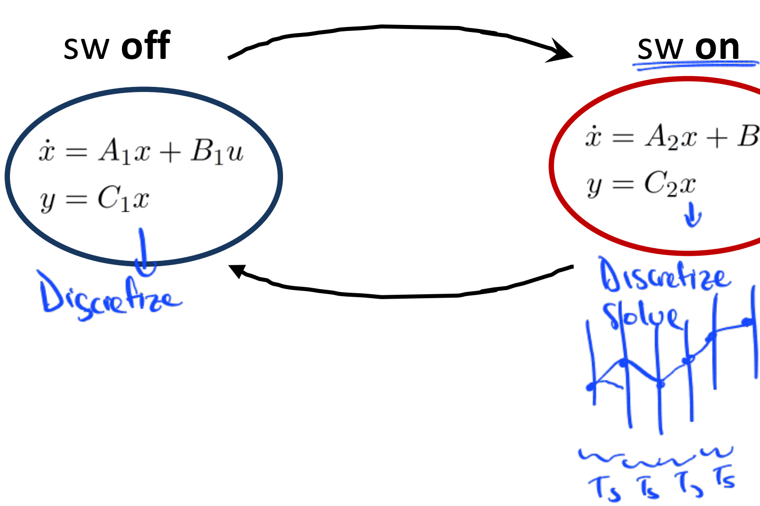
- For N switches, there will be 2^N different systems of the form:

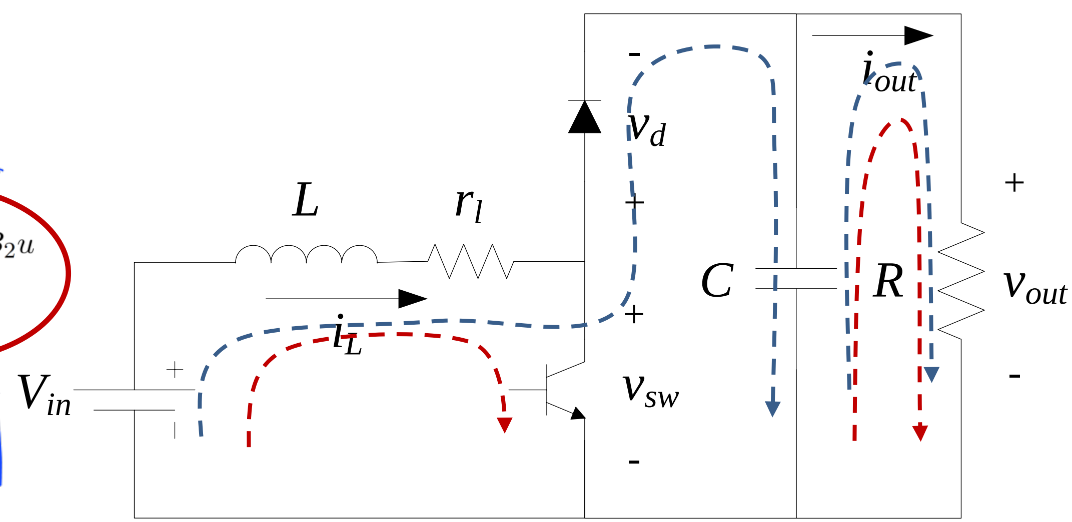
$$\dot{x} = A_i x(t) + B_i u(t)$$
$$y = C_i x(t), \quad i \in \{1, \ldots, 2^N\}$$

N switches
2^N state
Space Models.

$$\dot{x} = f_i(t, x, u)$$
$$y = h_i(t, x, u), \quad i \in \{1, \ldots, 2^N\}$$

- * Discretize the system and solve *
- **Advantages**: model can be very accurate
- **Disadvantages**: Large number of matrices to be stored, instability problems





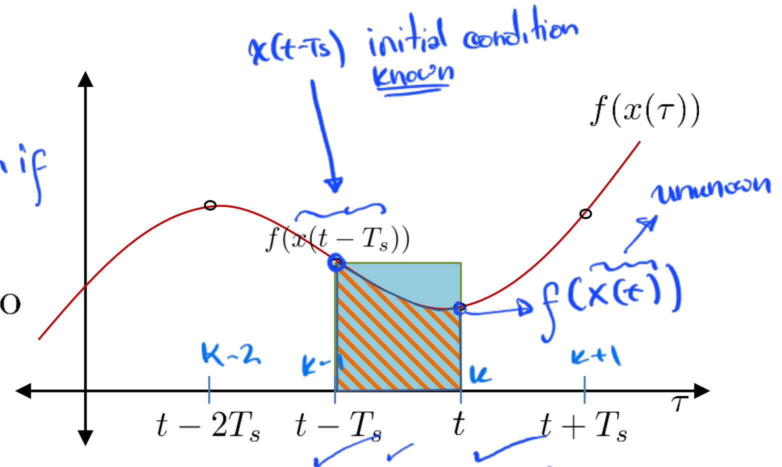
"Explicit" Integration Methods

- Consider a general nonlinear system: $x \in \mathbb{R}^n$

$$* \quad \dot{x} = f(x) \quad *$$

$x(t)$ is a solution if $\dot{x}(t) = f(x)$

- What are some ways to approximate the solution to this ODE?



$$\dot{x} = f(x) \Rightarrow \frac{dx}{dt} = f(x) \Rightarrow \int_{t-T_s}^{t} dx = \int_{t-T_s}^{t} f(x)\, dt$$

$$\Rightarrow x(t) \approx x(t-T_s) + \underbrace{T_s \cdot f(x(t-T_s))}_{\text{Area of rectangle.}}$$

Taylor (Series) Based Methods

$t - T_s \triangleq K-1$

$t \triangleq K \qquad K \in \mathbb{Z}$

$t + T_s \triangleq K+1$

Forward Euler (1st order Method)

Expand $x(t)$ using Taylor series around the initial condition $x(k)$ (initial condition) $\Rightarrow x(k+1)$

$$x(k+1) = x(k) + \underline{\dot{x}(k) \cdot T_s} + \frac{\ddot{x}(k)}{2} \cdot T_s^2 + \text{H.O.T.}$$

$0 < T_s < 1$

$$\boxed{x(k+1) \approx x(k) + T_s \cdot f(x(k))}$$ Forward Euler (Explicit)

$e_L \to 0$ as $T_s \to 0$

What is the approximation error? (Local and Global)

Based on Taylor's theorem

$$x(k+1) = x(k) + T_s \dot{x}(k) + \frac{T_s^2}{2} \ddot{x}(\xi) \qquad \xi \in [0, T_s]$$

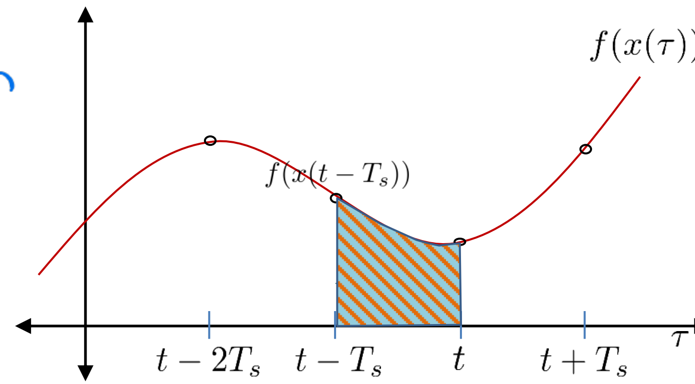
$\Rightarrow$ Local Error $\quad e_L = \frac{T_s^2}{2} \ddot{x}(\xi) \quad O(T_s^2)$

Global Errors $\quad e_G \propto T_s \quad O(T_s)$

Explicit Integration Methods

- Consider a general nonlinear system:

$$\dot{x} = f(x) \qquad f(x) = Ax \qquad x \in \mathbb{R}^n$$



- What if the system is LTI? $\dot{x} = Ax$? $\quad \mathrm{Re}\{\lambda\} < 0$

Forward Euler Approximation: $x(k+1) = x(k) + T_s \cdot f(x(k))$

(does not preserve stability)

LTI: $x(k+1) = x(k) + T_s A\, x(k)$ FE

$$\boxed{x(k+1) = (I + T_s A)\, x(k)} \quad \Longleftrightarrow \quad x(k+1) = A_d\, x(k) \qquad A_d \triangleq I + T_s A$$

Stability of a Discrete State Space System

$x_{k+1} = A_d x_k \qquad x_0 = \text{i.c. (unknown)}$

$x_1 = A_d x_0$

$x_2 = A_d x_1 = A_d(A_d x_0) = A_d^2 x_0$

$x_3 = A_d^3 x_0$

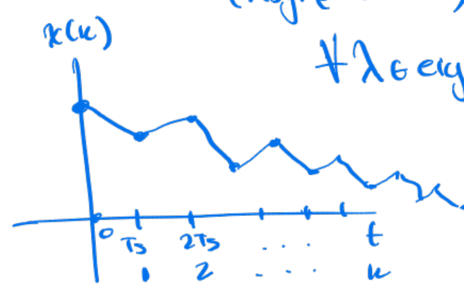
$\vdots$

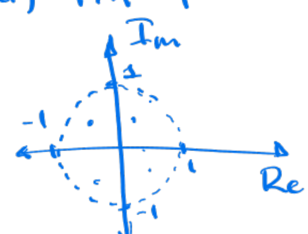
$x_n = A_d^n x_0$

- Under what conditions will $x_k \to 0$ as $k \to \infty$ for $x_0 \neq 0$

(Asymp. Stable) $\quad \lambda \in \mathbb{C}$

$\forall \lambda \in \mathrm{eig}(A_d) \quad |\lambda| < 1$





for $n=1 \quad \lambda \in \mathbb{R}$

$x_{k+1} = \lambda x_k$

$x_1 = \lambda x_0$

$x_2 = \lambda^2 x_0$

$\vdots$

$x_n = \lambda^n x_0$

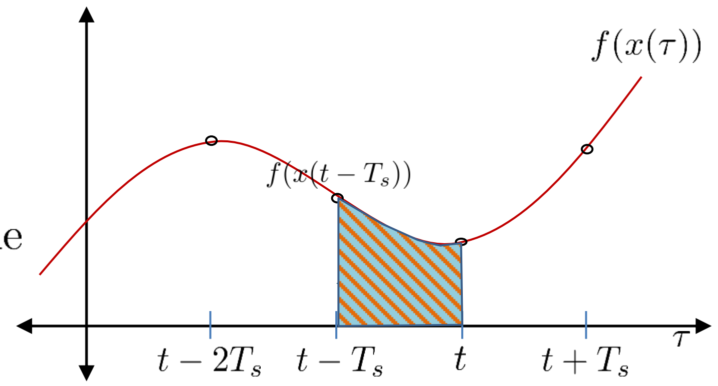
$|\lambda| < 1$

Explicit Integration Methods

- Consider a general nonlinear system:

$$\dot{x} = f(x)$$

- What are some different ways to approximate the solution to this ODE?



N^{th} Order Taylor Approximation Methods:

$$x(k+1) = x(k) + T_s \dot{x}(k) + \frac{T_s^2}{2} \ddot{x}(k) + \frac{T_s^3}{3!} \dddot{x}(k) + \ldots$$

- For $N=1$ (1st order truncation) $\Rightarrow$ Forward Euler

- In general

$$x(k+1) = x(k) + T_s \cdot F_d^{(N)}(x(k)) \quad \text{where} \quad F_d^{(N)} = f(x(k)) + \frac{T_s}{2}\dot{f}(x(k)) + \frac{T_s^2}{2}\ddot{f}(x(k)) + \ldots + \frac{T_s^{N-1}}{N!} f^{(N-1)}(x(k))$$

Runge Kutta Based Methods

Explicit Integration Stability

- Using **Forward Euler** for a linear system, we can obtain the following:

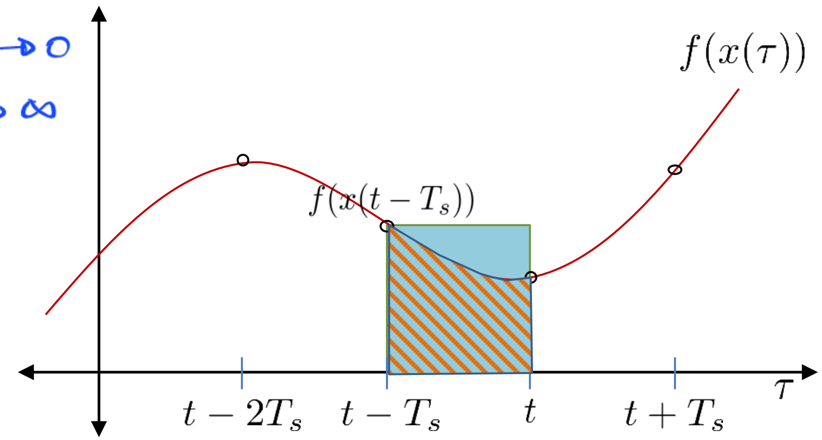
$\dot{x} = -3x \quad \lambda = -3 < 0$

$x(t) = e^{-3t} x(0)$

$$\dot{x} = \lambda x, \quad x(0) = x_o, \quad x \in \mathbb{R} \qquad \lambda \in \mathbb{R}$$

$$\boxed{x(k) = (1 + \lambda T_s) x(0)} \quad \text{Forward Euler} \qquad \text{will } x_k \to 0 \text{ as } k \to \infty$$

$$x(t) = e^{\lambda t} x(0) \qquad \text{Actual solution}$$



- For the cont. system to be **stable**, the eigenvalue must be less than or equal to 0, i.e.

$$\lambda \leq 0$$

- If cont. system is stable, **will the Forward Euler approximation always be stable?**

Forward Euler: $x_k = (1 + \lambda T_s) x_o \quad x_k \to 0$ as $k \to \infty$

$x_1 = (1 + \lambda T_s) x_o$

$x_2 = (1 + \lambda T_s)^2 x_o$

$\vdots$

$x_n = (1 + \lambda T_s)^n x_o$

For a discrete system to be Asymp. Stable $\underbrace{|1 + \lambda T_s| < 1}$

$-1 < 1 + \lambda T_s < 1 \qquad$ we know $\lambda < 0, \quad \lambda = -|\lambda| < 0$

$\underbrace{-1 < 1 - |\lambda| T_s < 1} \qquad |\lambda| T_s < 2$

For stability:

$$\boxed{T_s < \frac{2}{|\lambda|}}$$

if $T_s \geq \frac{2}{|\lambda|}$ discrete FE is not stable!

Forward Euler Example

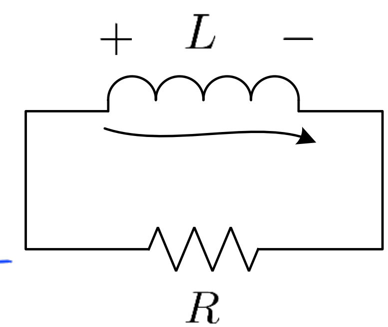
- Use Forward Euler to discretize an inductor/resistor

$i_L(0) = I_0$

if $R, L > 0$ $\quad \lambda = \underbrace{\frac{-R}{L}}_{} < 0$

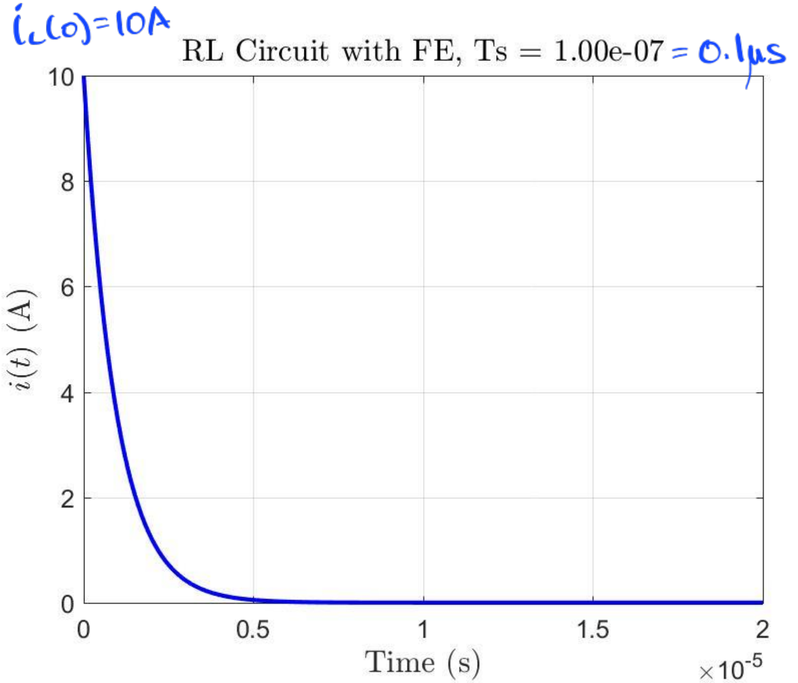
$$\boxed{\frac{di}{dt} = -\underbrace{\frac{R}{L}}_{} i(t)} \qquad i(k+1) = \left(1 - \frac{R}{L} T_s\right) i(k)$$

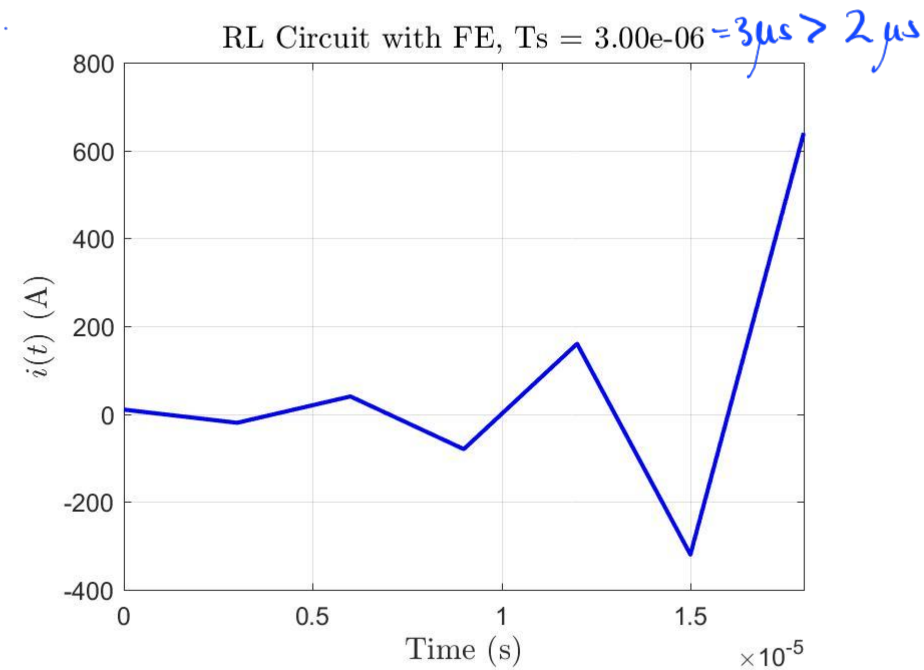
Forward Euler Approx.



- If $R = 10\ \Omega$ and $L = 10\ \mu H$ then $\underbrace{T_s \leq 2\ \mu s!}_{}$ $\Rightarrow T_s < \frac{2}{|\lambda|} = \frac{2 \cdot L}{R}$

$i_L(0) = 10A$





Implicit Integration Methods

- Consider a general nonlinear system:

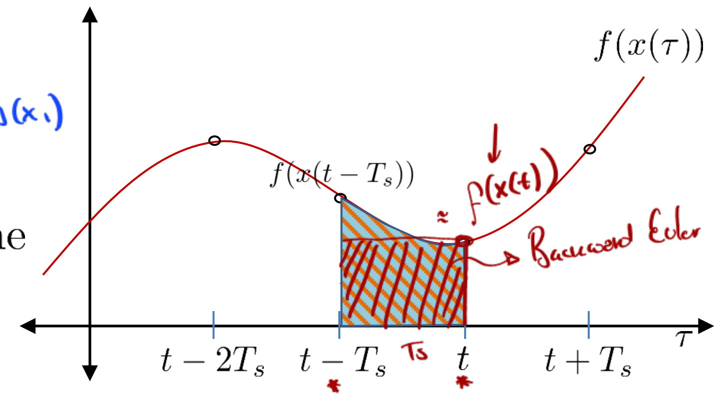
$$\dot{x} = f(x)$$

Example

$\dot{x}_1 = 3x_1x_2^2 + \cos(x_1)$

$\dot{x}_2 = \sin(x_1)$

- What are some different ways to approximate the solution to this ODE?



$k = 0, 1, 2, \ldots,$

Backward Euler Approximation

$$\dot{x} = f(x) \longrightarrow \frac{dx}{dt} = f(x) \rightarrow \int_{kT_s}^{(k+1)T_s} dx = \int_{kT_s}^{(k+1)T_s} f(x)\, dt$$

$$\Rightarrow \overset{?}{x(k+1)} - \overset{\checkmark}{x(k)} \overset{BE}{\approx} T_s f(\overset{?}{x(k+1)})$$

initial condition $x(k) = x_0$ (known)

$$\Rightarrow \boxed{x(k+1) = x(k) + T_s f(x(k+1)) \quad \text{[Implicit euqtion]}}$$

$$x(k) = \begin{pmatrix} 3 \\ 2 \end{pmatrix} \longrightarrow \begin{pmatrix} x_1(k+1) \\ x_2(k+1) \end{pmatrix} = \begin{pmatrix} 3 \\ 2 \end{pmatrix} + T_s \begin{pmatrix} 3x_1(k+1)x_2^2(k+1) + \cos(x_1(k+1)) \\ \sin(x_1(k+1)) \end{pmatrix}$$

$$\rightarrow \begin{aligned} x_1(k+1) &= 3 + T_s\left(3x_1(k+1)x_2(k+1)^2 + \cos(x_1(k+1))\right) \\ x_2(k+1) &= 2 + T_s\left(\sin(x_1(k+1))\right) \end{aligned}$$

Set of nonlinear functions

n unknowns – n equations.

Analytical

Numerical Methods

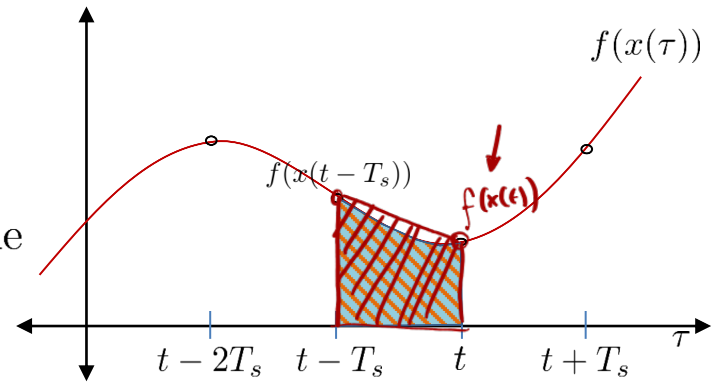
- Gauss-Seidel
- Newton Raphson

Implicit Integration Methods

- Consider a general nonlinear system:

$$\dot{x} = f(x)$$

- What are some different ways to approximate the solution to this ODE?



Trapezoidal Method

$$\frac{dx}{dt} = f(x) \xrightarrow{\approx} \boxed{x(k+1) = x(k) + \frac{T_s}{2}\left(f(x(k)) + f(x(k+1))\right)}$$

- One major advantage of Implicit Integration methods, in particular Backward Euler is that they preserve stability for any T_s

Continuous System is A.Stable → BE Approx. is also A.Stable

For LTI Systems $\dot{x} = Ax = f(x)$ $A \in \mathbb{R}^{n \times n}$ $x \in \mathbb{R}^n$ $x(k) = x_k$ known/initial condition.

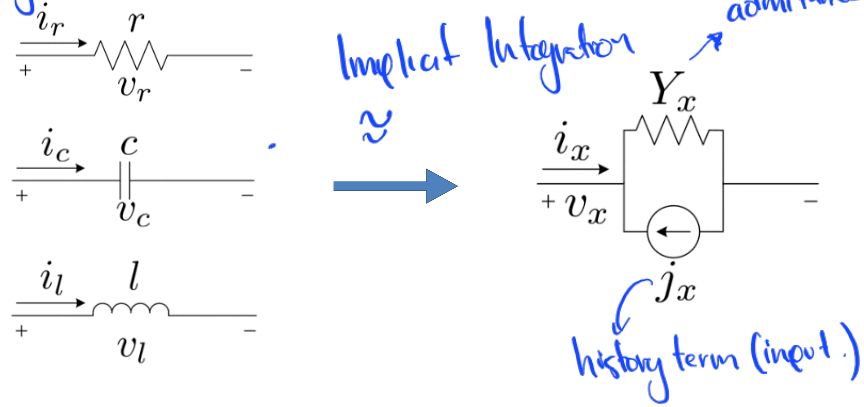
$$x(k+1) = x(k) + T_s\left(Ax(k+1)\right) \longrightarrow x(k+1) - T_s A x(k+1) = x(k) \rightarrow (I - T_s A)\, x(k+1) = x(k)$$

$$\Rightarrow x(k+1) = (I - T_s A)^{-1} x(k)$$

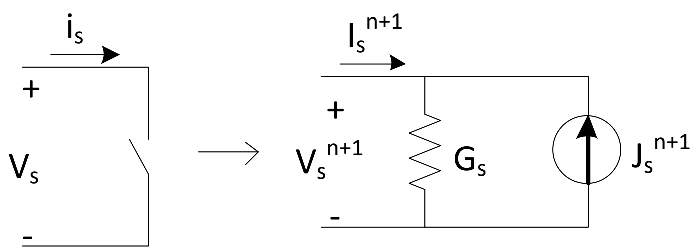
Method 2: Modified Nodal Analysis

Electromagnetic Transient Simulation

- Uses **implicit** integration: BE, Trapezoidal, etc.
- Represent passive components as:



- **Represent a switch by a resistor in parallel with a current source.**



$$j_s^{n+1} = \begin{cases} -i_s^n & \text{if} \quad s^{n+1} = 1 \\ G_s V^n & \text{if} \quad s^{n+1} = 0 \end{cases}$$

$V_L = L\frac{di}{dt} \rightarrow$ BE $\quad i(k+1) = i(k) + \frac{T_s}{L} V_L(k+1)$

Inductor

$$i_L^{n+1} \approx \frac{T_s}{L} v_L^{n+1} + \underline{i_L^n} = G_L v_L^{n+1} - \underline{j_L^{n+1}}$$

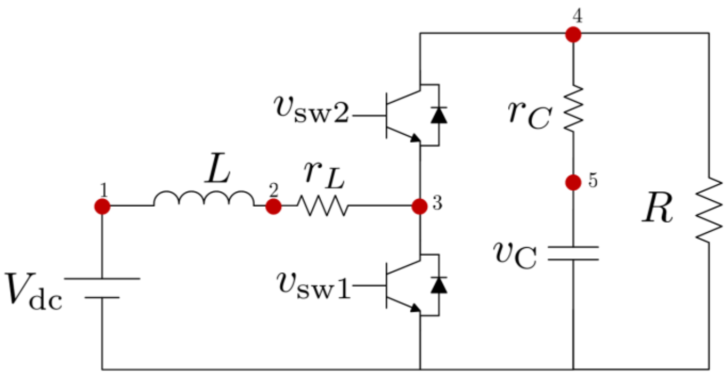
Capacitor

$$i_C^{n+1} \approx \frac{C}{T_s} v_C^{n+1} - \underline{\frac{C}{T_s} v_C^n} = G_C v_C^{n+1} - \underline{j_C^{n+1}}$$

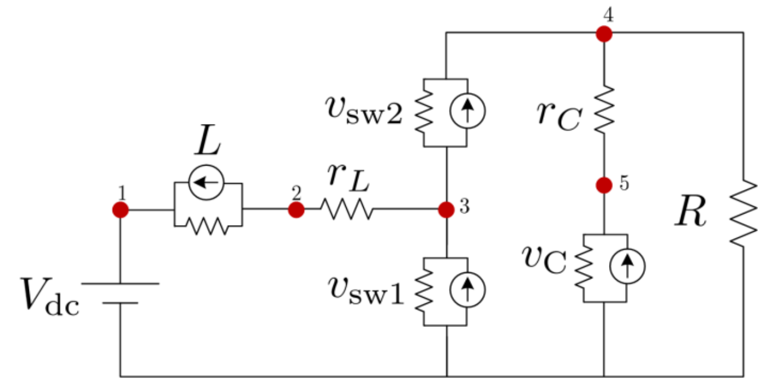
P. Pejovic and D. Maksimovic, "A method for fast time-domain simulation of networks and switches," *IEEE Trans. On Power Electronics,* vol. 9, no. 4, pp. 449-456, Jul. 1994

Modified Nodal Analysis (cont'd)

Example of a boost converter in MNA:



BE



I = YV

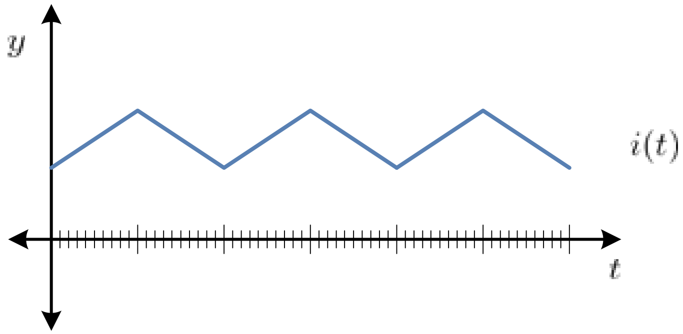
TABLE I. Netlist Example

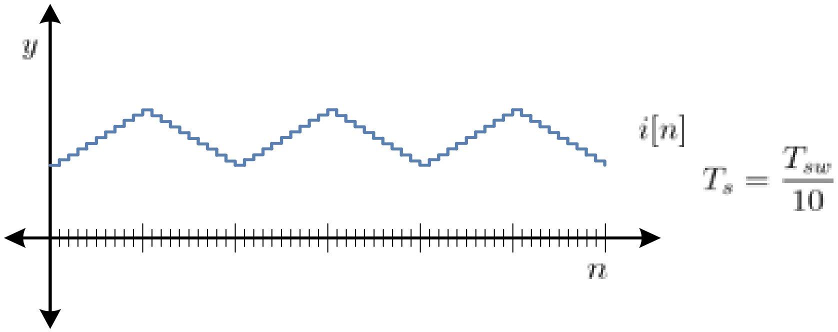
Element	In	End	Value
r_L	2	3	1 mΩ
r_C	4	5	1 mΩ
R	4	0	2 Ω
L	1	2	1 mH
C	5	0	2.5 mF
S_1	3	0	0.5 ℧
S_2	3	4	0.5 ℧
V_{dc}	1	0	50 V

$$
\left(\begin{array}{ccccc:c}
Y_L & -Y_L & 0 & 0 & 0 & 1 \\
-Y_L & Y_L + Y_{rL} & -Y_{rL} & 0 & 0 & 0 \\
0 & -Y_{rL} & Y_{rL} + Y_{s1} + Y_{s2} & -Y_{s2} & 0 & 0 \\
0 & 0 & 0Y_{s2} & Y_R + Y_{s2} + Y_{rC} & -Y_{rC} & 0 \\
0 & 0 & 0 & -Y_{rC} & Y_{rC} + Y_C & 0 \\
\hdashline
1 & 0 & 0 & 0 & 0 & 0
\end{array}\right)
\begin{pmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \\ v_5 \\ i_{dc} \end{pmatrix}
=
\begin{pmatrix} j_L \\ -j_L \\ j_{s1} + j_{s2} \\ -j_{s2} \\ j_C \\ V_{dc} \end{pmatrix}
$$

Limitations of CPU based Simulation

- Regular CPU based real time simulation of power electronic circuits has a minimum time step of ~10 *us* which is not enough to model power converters operating at >10 kHz





For example:

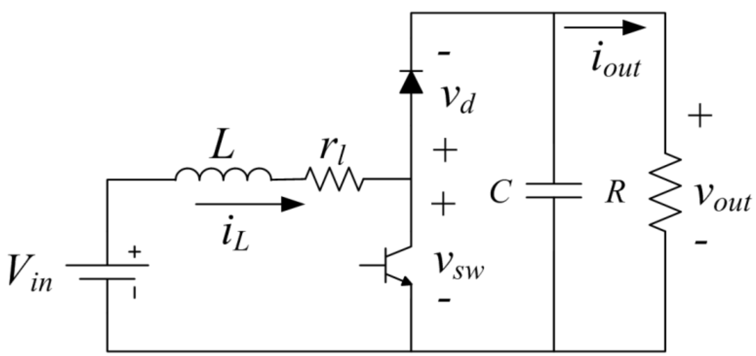
$F_{sw} = 100 \text{ kHz} \;\Rightarrow\; T_{sw} = 10 \ \mu\text{s}$ Simulation time step should be: $T_s < 1 \ \mu\text{s}$

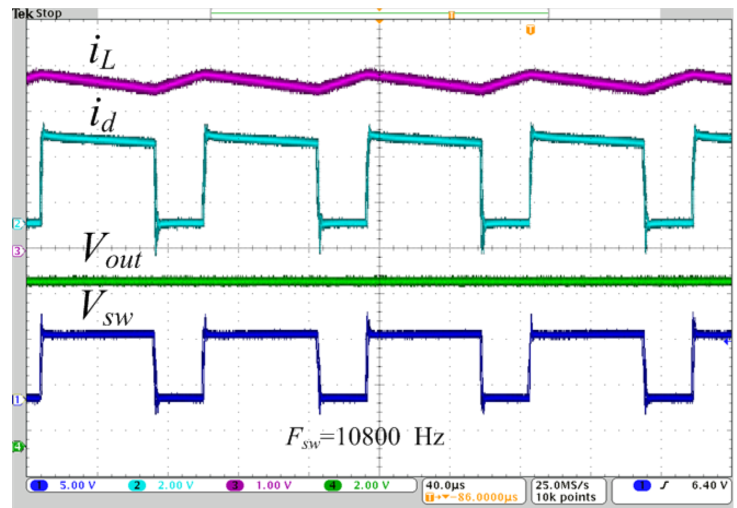
- **Possible Solutions:**
  - **GPU:** Typical time steps $T_s \approx 1\mu\text{s}$
  - **FPGA:** Typical time steps $T_s < 1\mu\text{s}$

FPGA based Simulation

- Types of power converter modeling
  - State space methods: small on resistance, large off resistance
  - State machine (logic) for modeling switches
  - **Modified nodal analysis** EMT , RTDS

I= YV



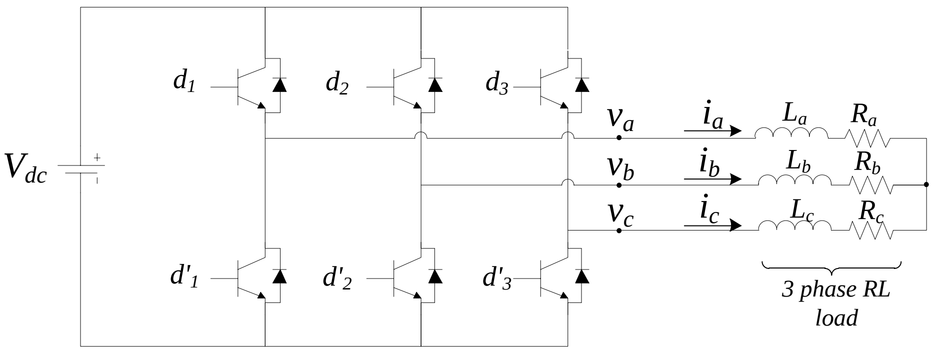


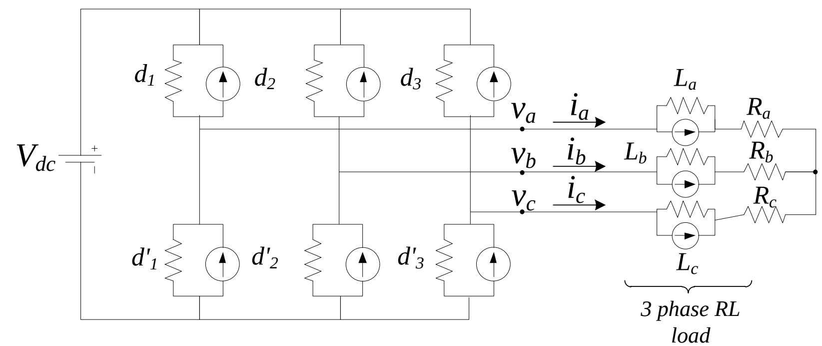
- **Implemented on Virtex 6 FPGA at a time step T_s = 200 ns**
- **Detailed switching transients possible**

- **Challenges with FPGA based simulation**
  - Complex low level programming is needed
  - **No mature software is available for FPGA based implementation of numerical integration techniques**

Modified Nodal Analysis (cont'd)

Example of an inverter in MNA:





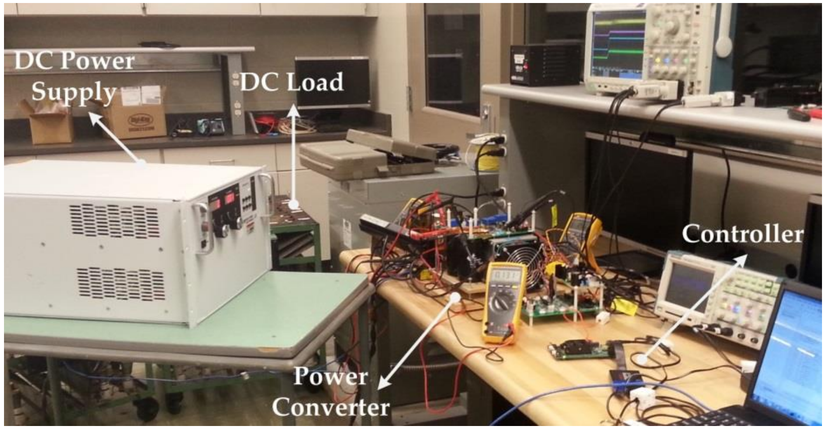
- Derive the equations for each node in the circuit based on an admittance matrix.
- The main advantage is that *A* matrix is constant, only terms in *b* (vector) change.

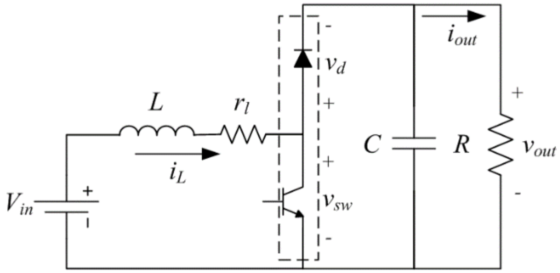
$$Ax^{n+1} = b^n \longrightarrow x^{n+1} = (A)^{-1} b^n$$

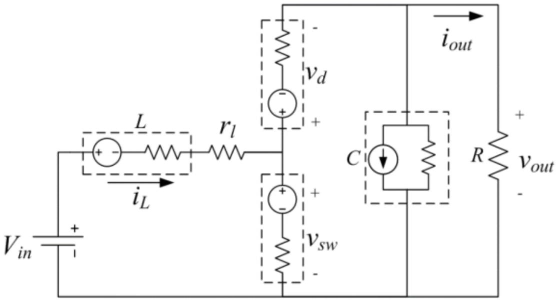
***A* is constant**

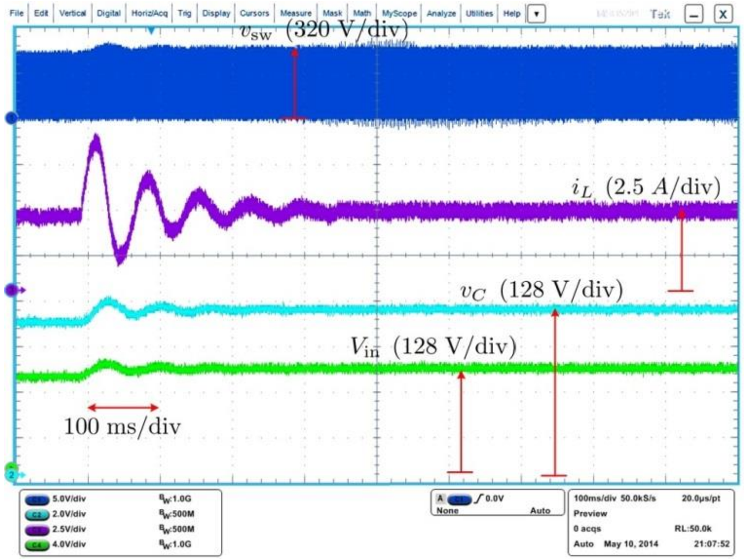
Example: Boost Converter

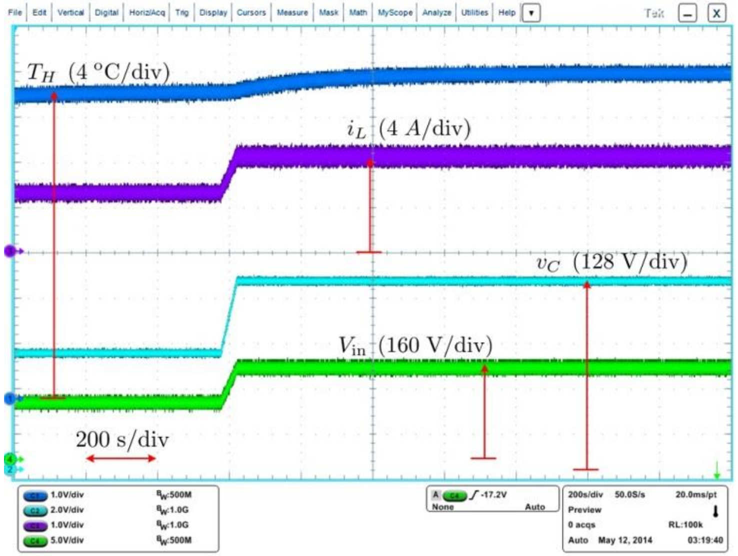
- Model of the boost converter using the proposed method:





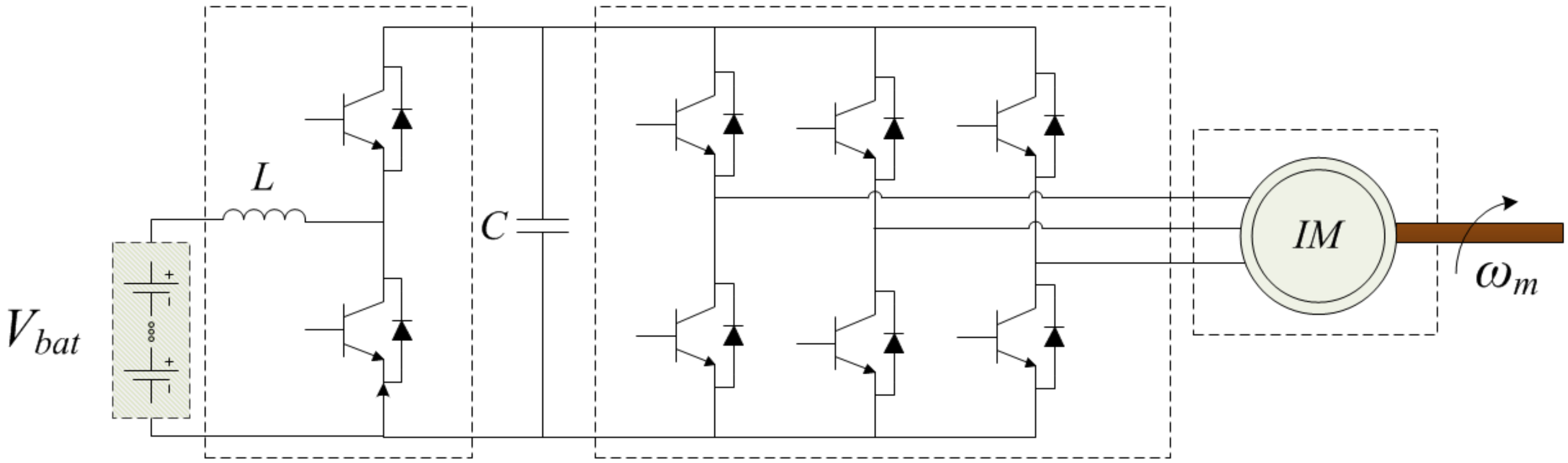






Example: Induction Machine Drive

- In order to control the EV motor speed, torque, etc. A typical three phase converter system is added to the system:



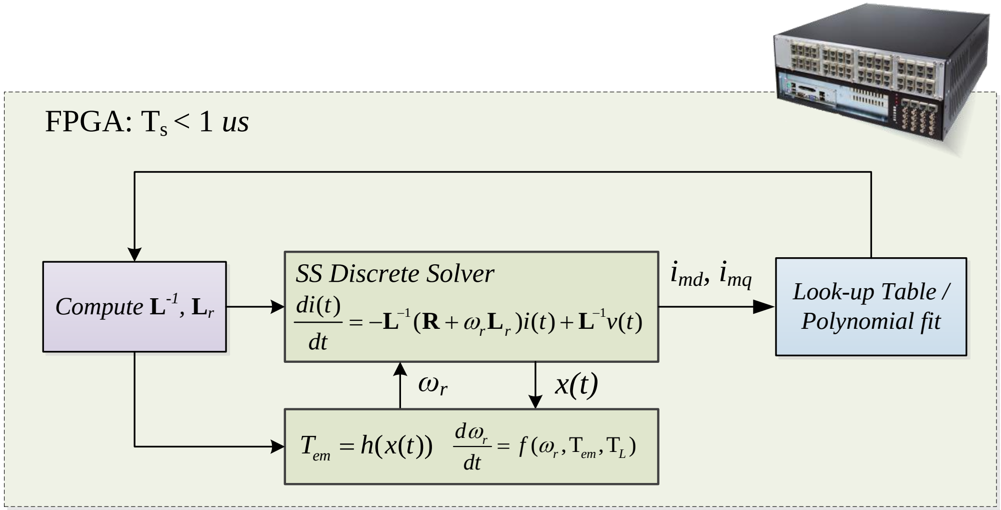
- In order to **increase efficiency** and **minimize losses,** several aspects can be improved:
  - ✓ ***Offline:*** Structural, design, factory set
  - ✓ ***Online:*** Model based control

Induction Machine Modeling

- A typical *direct* and *quadrature* (dq) model for an induction motor is in the following form:

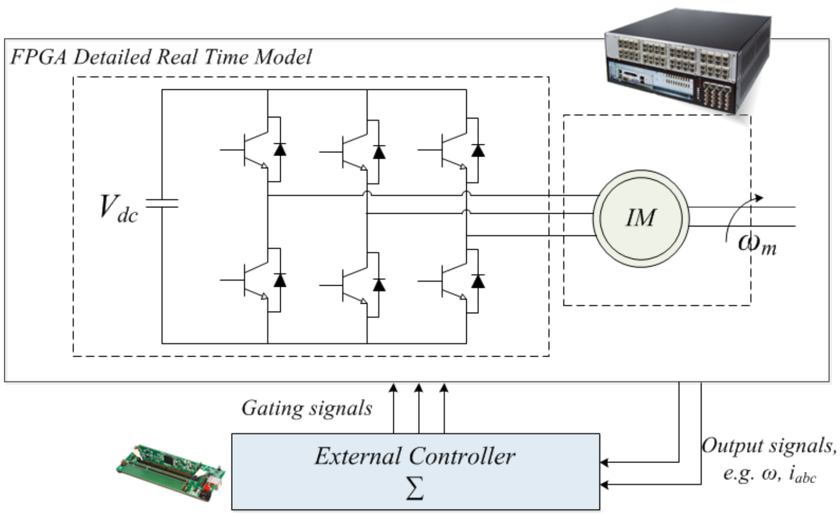
$$v(t) = \mathbf{R}i(t) + \omega_r \mathbf{L}_r i(t) + \mathbf{L}\frac{di(t)}{dt}$$

$$\mathbf{L}_r = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & L_m & 0 & (L_{lr}+L_m) \\ -L_m & 0 & -(L_{lr}+L_m) & 0 \end{pmatrix} \quad \mathbf{L} = \begin{pmatrix} L_{ls}+L_{dd} & L_{dq} & L_{dd} & L_{dq} \\ L_{dq} & L_{ls}+L_{qq} & L_{dq} & L_{qq} \\ L_{dd} & L_{dq} & L_{lr}+L_{dd} & L_{dq} \\ L_{dq} & L_{qq} & L_{dq} & L_{lr}+L_{qq} \end{pmatrix}$$

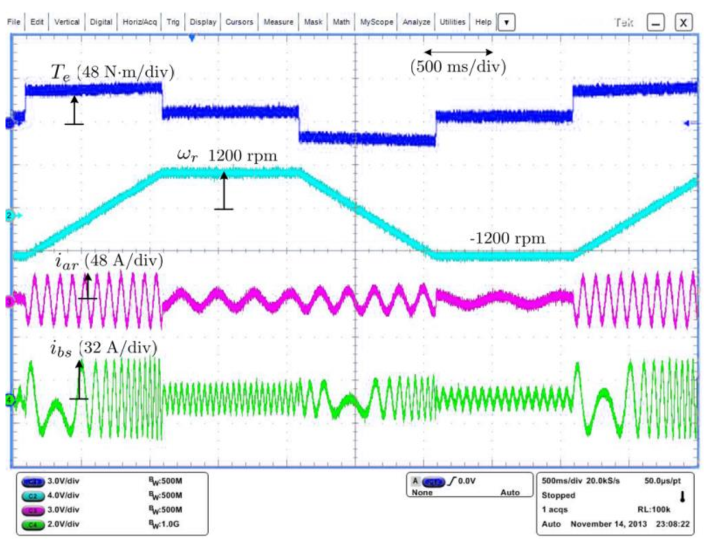


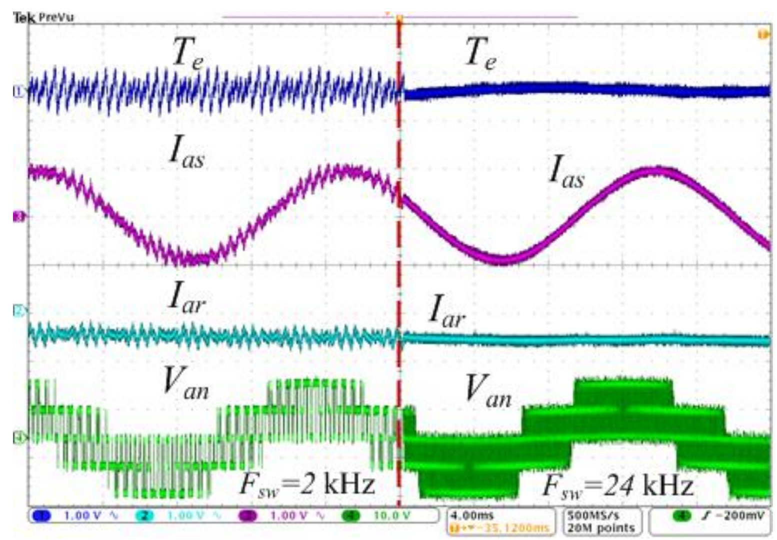
Example and Simulation Results

- Implemented the following machine model with three phase inverter.



R_s	1.97 Ω	R_r	2.82 Ω	J	0.11 kgm^2
L_{ls}	10.23 mH	L_{lr}	8 mH	D	0.01
V_{abc}	465 V	f_{abc}	[30 70] Hz	P	2

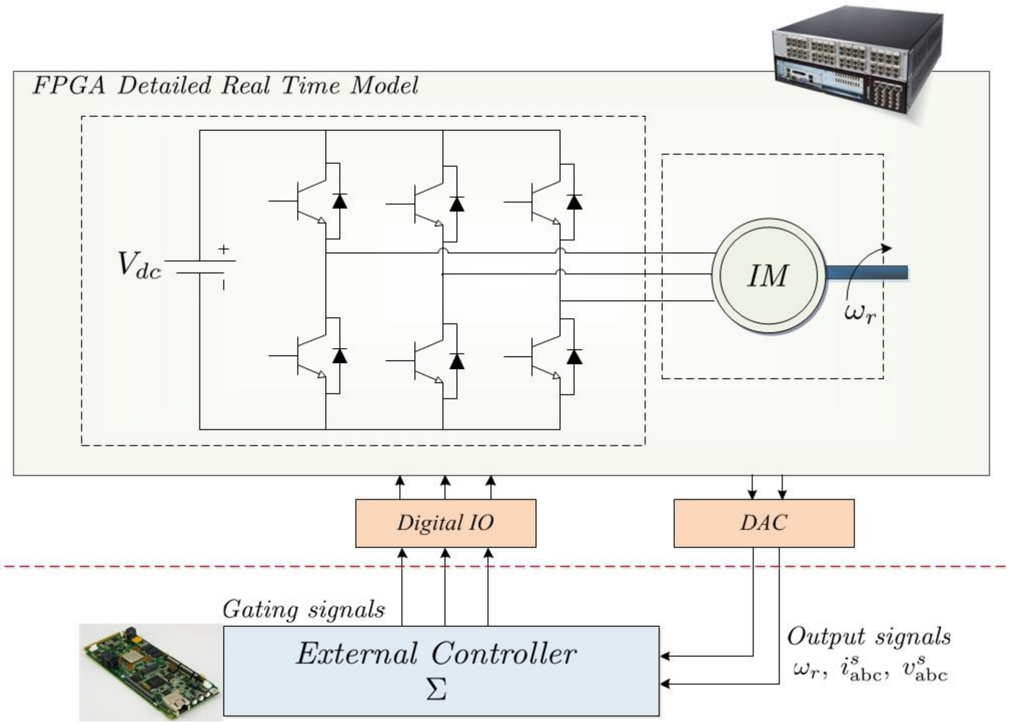




Control Hardware-in-the-loop

- **Controller hardware-in-the-loop**: the plant is simulated with the real time platform to test an External Control Unit (ECU)

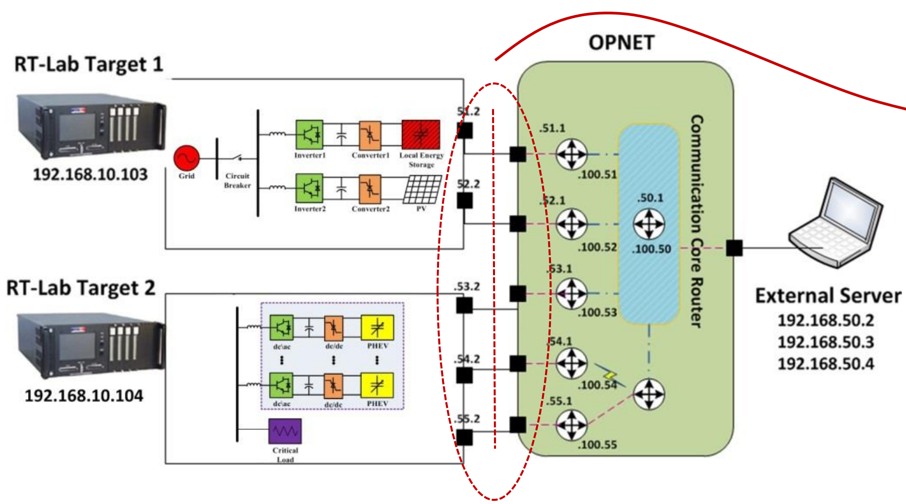
- **Advantages:**
  - Close to real evaluation of control algorithms
  - Flexibility in testing all normal operations and failure modes
  - Reduced product development time and cost



- **Main challenges**
  - **Fidelity of the real-time model**
  - **Interfacing issues, speed of DAC, ADC, and DIO**
  - **For high switching frequency power converters, small time steps are required – ps to ns range**

System-in-the-loop for Communication Network

- System-in-the-loop based real-time simulation of communication can be used in parallel with an actual electric power system or a RT model
- Commercially available network simulators offer great flexibility in the modeling of the network:
  - Cyber attacks
  - Packet losses, latency, etc.
- **One of the main challenges is interfacing the real system or electrical RT model, with the communication network, e.g.**

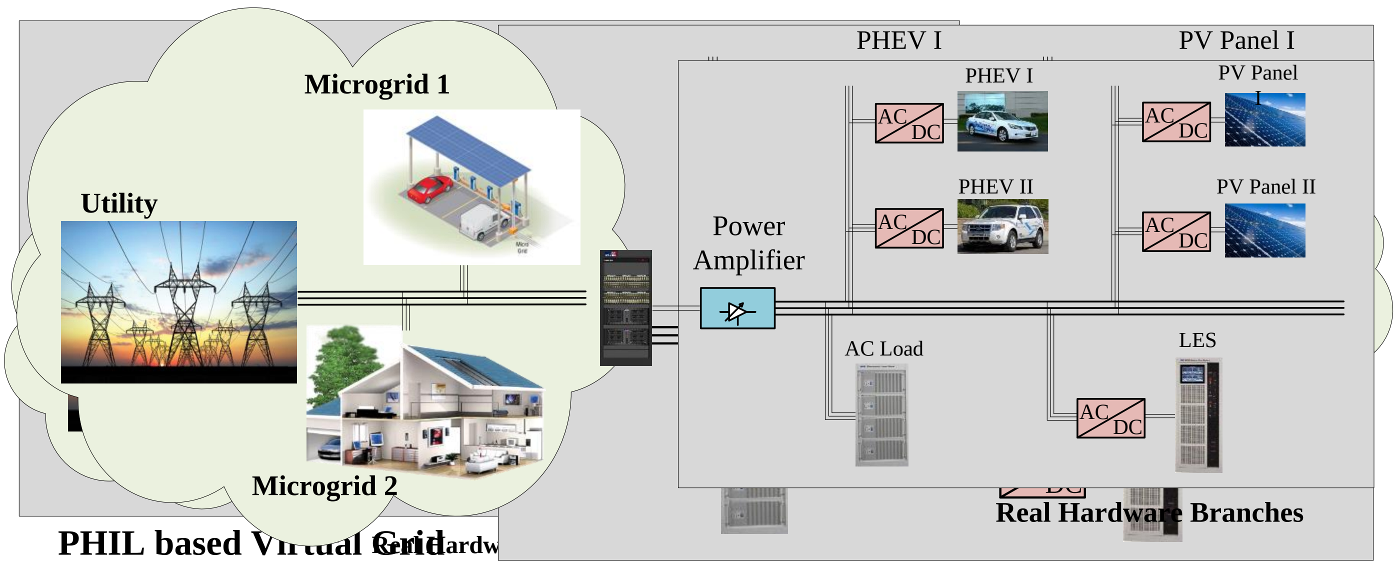


Physical Ethernet links (UPD – TCP) to link the "actual system" with the "communication network"

Delays ~ 2 to 3 us

Power Hardware-in-the-loop

- Flexible and reconfigurable <u>electric power network</u> with real-time simulation based Power Hardware-in-the-Loop (PHIL) unit
  - *Simulate one or several subsystems of a mircogrid; or*
  - *Simulate a scaled-down utility grid, and study the interaction between microgrid and the utility grid; or*
  - *Simulate one or more scaled-down microgrids, and study the interaction between different microgrids*

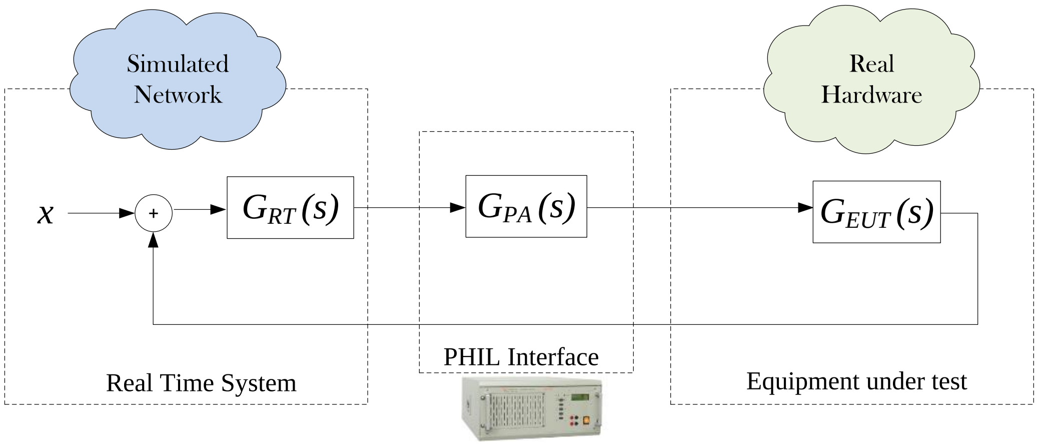


PHIL based Virtual Microgrids and the main utility lines.

Real Hardware Branches

PHIL Challenges

- The "link" connecting the real system and the virtual model is defined by the **power amplifier** dynamics
- The complete system can be described by the figure
- Ideally $G_{\mathrm{PA}}(s) = 1$
- Realistically, the PA unit adds:
  - Latency - delays
  - Bandwidth limitation
  - External dynamics



- These external dynamics deteriorate the fidelity of the system and can drive an otherwise stable system to instable

Typical specification of the power amplifier:

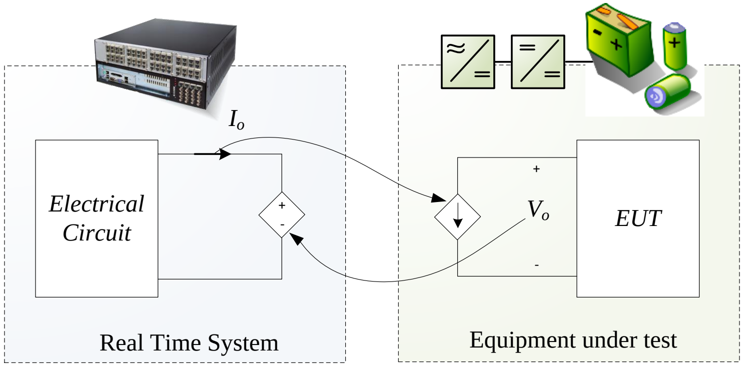
- **5 – 30 kHz** Large signal bandwidth
- **Slew rate 52 V / µs**

Not fast enough for load dynamics in aircraft and other types of vehicle applications.

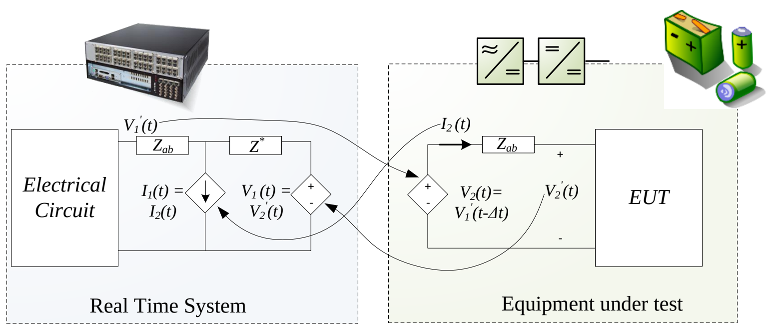
PHIL Challenges (cont'd)

- Another challenge which arises in using power amplifiers, is finding the best (robustness, accuracy, stability) interconnection techniques:

- Two techniques shown are:
  - **Ideal transformer model:** Straightforward, good accuracy but poor stability performance
  - **Damping impedance method:** Good accuracy and stability performance but depends on impedance z^* choice.



Ideal Transformer Model



Damping Impedance Method

Although only two methods are presented, other methods exists or can be discovered to improve accuracy, stability and robustness

HIL Methods

- There is a need for developing multi-time-scale real time simulation systems
- Challenges of HIL methodologies are listed as follows

HIL Methodologies	Challenges
CHIL	Fidelity of the real-time models
	Interfacing issues by ADC, DAC, and DIO
	Small time step models with paralleled FPGAs
SITL	Latency in the interconnecting links
PHIL	Fidelity of the real time model
	Added power amplifier dynamics
	Interconnection methods

Outline

- **HVDC Overview**
- **Real Time Simulation and Hardware in the Loop (HIL)**
- **Digital/Discrete Implementation of Controllers**