EINDHOVEN UNIVERSITY OF TECHNOLOGY

A New Modulation Method based on Switching Losses Minimization for DC-AC Inverters

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POWER ELECTRONICS
ENERGY STORAGE
Power Electronics & Energy Storage event
27 juni 2023 | 1931 Congrescentrum 's-Hertogenbosch

What I will talk about …

- Multilevel DC-AC inverters
- Preliminaries
- Proposed modulation method
- Simulation results
- Conclusion

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Multilevel DC-AC inverter

Many *applications*:

- photovoltaic systems
- high-voltage power transmissions
- electric motor drives

Characteristics:

- Controlled AC *voltage source*
  - composed of >2 levels
  - drives desired load currents

Three-level NPC inverter

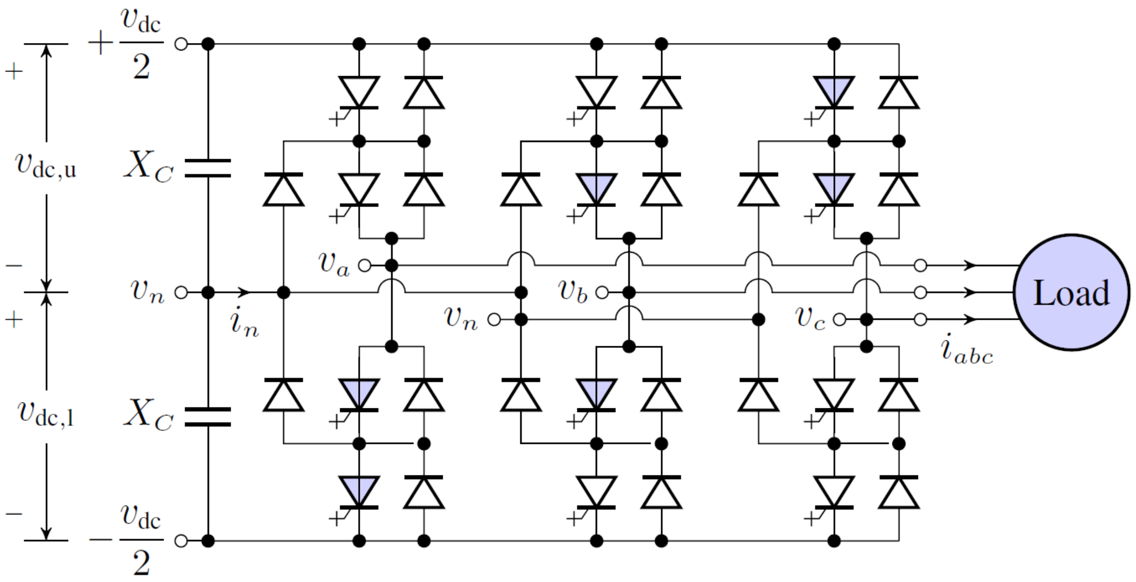
- Applications of few MW and kV

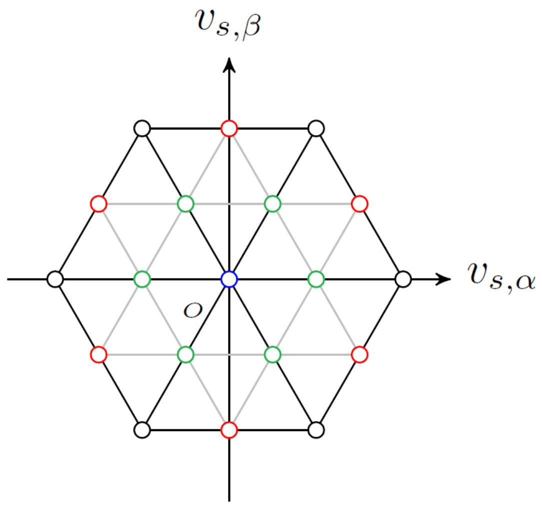
- Phase voltages
  $v_x = \{-v_{dc,l}, v_n, v_{dc,u}\}$

- 27 switch positions
  $u_{abc} = \{-1,0,1\}^3$

- *Clarke* transformation:

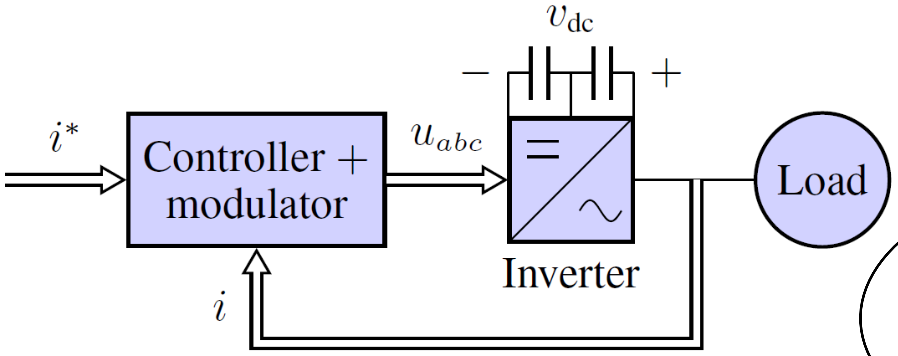
$$v_{\alpha\beta} = P v_{abc}, \text{ where } P = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}$$



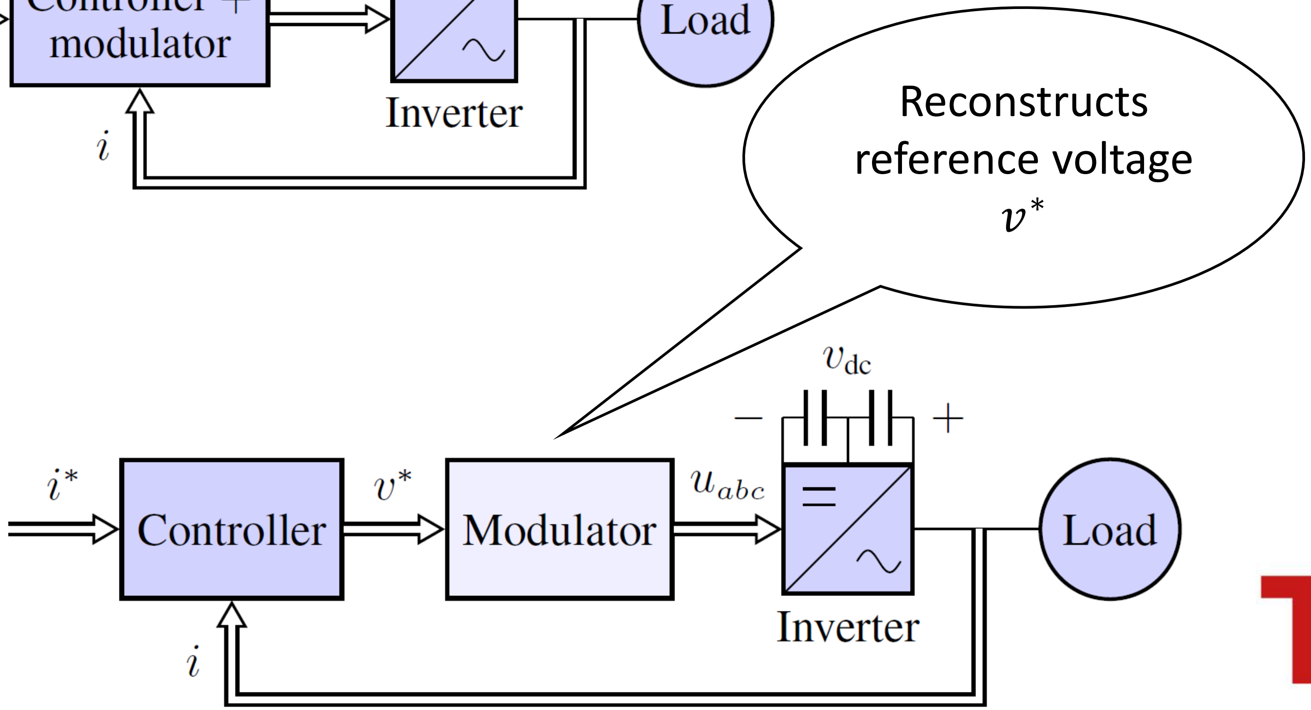


Load current control schemes

- *Direct* control:



- *Indirect* control:



Trade-off switching losses and THD

- Direct control: *trade-off*

- Indirect control: so far *performance* and *constraint* satisfaction
  - *Trade-off* done by modulator → focus of this presentation

- Modulators (implicit trade-off):
  - *Soft switching type* modulation (switches around zero currents)
  - *Discontinuous PWM* (reduces number of switchings)
  - *Space vector modulation* (small voltage jumps)

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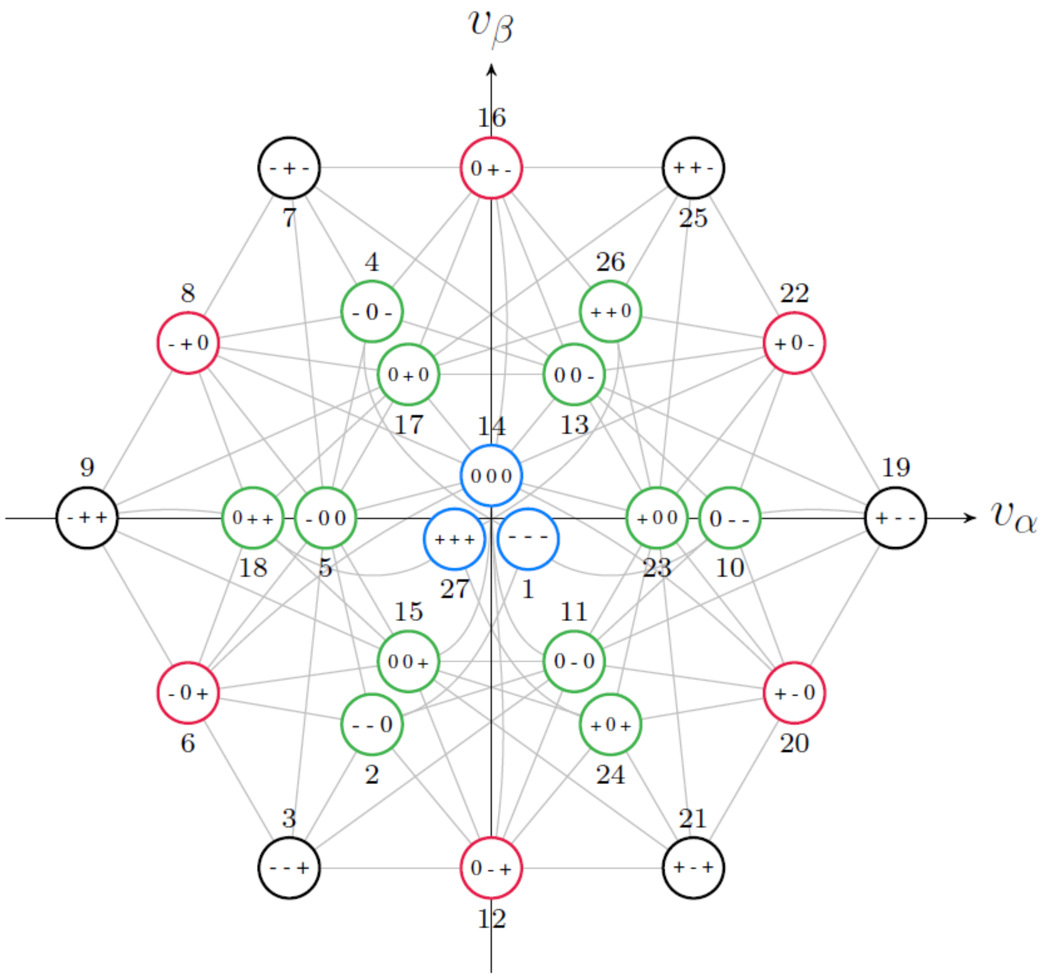
Three-level NPC inverter

- Switching *constraints*
  - Not directly between -1 and 1
  - In max 2 phase, in opposite inverter halves

- Neutral-point voltage *balancing*



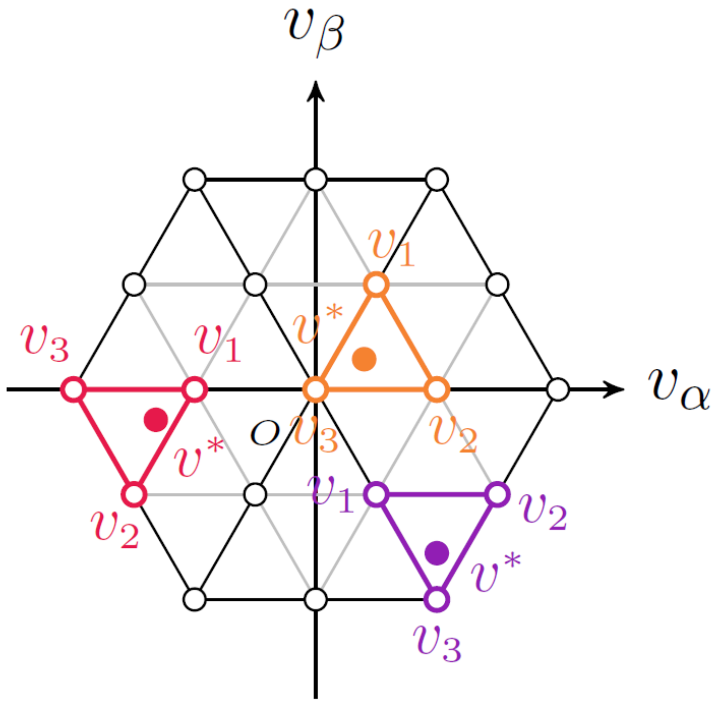
Space vector modulation

- The *closest* triangle with v_1, v_2, v_3

- For every *modulation cycle* T_s:

$$t_1 v_{1,\alpha} + t_2 v_{2,\alpha} + t_3 v_{3,\alpha} = T_s v_\alpha^*$$
$$t_1 v_{1,\beta} + t_2 v_{2,\beta} + t_3 v_{3,\beta} = T_s v_\beta^*$$
$$t_1 + t_2 + t_3 = T_s$$

- $t_1, t_2, t_3 \geq 0$



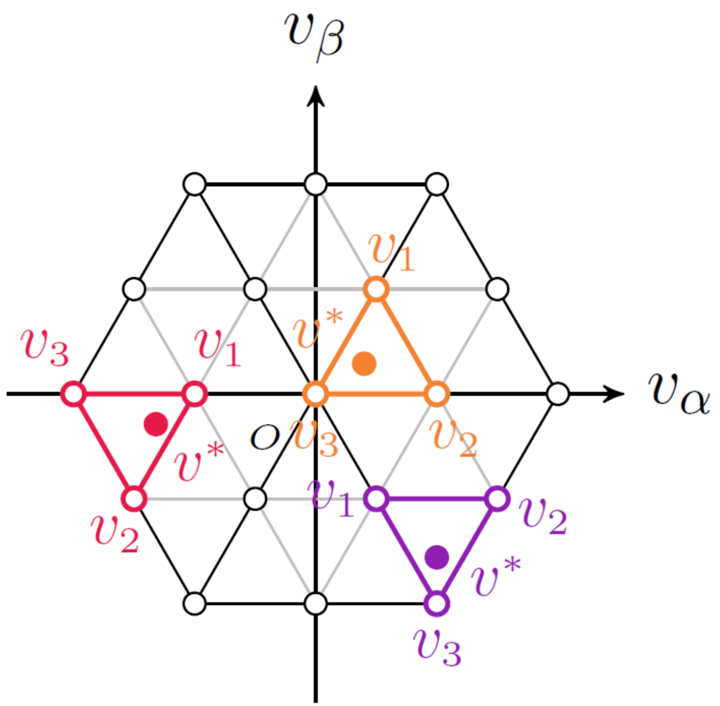
Space vector modulation

- The *closest* triangle with v_1, v_2, v_3

- Define $\bar{t} = \frac{t}{T_s}$, for every *modulation cycle* T_s:

$$\bar{t}_1 v_{1,\alpha} + \bar{t}_2 v_{2,\alpha} + \bar{t}_3 v_{3,\alpha} = v_\alpha^*$$
$$\bar{t}_1 v_{1,\beta} + \bar{t}_2 v_{2,\beta} + \bar{t}_3 v_{3,\beta} = v_\beta^*$$
$$\bar{t}_1 + \bar{t}_2 + \bar{t}_3 = 1$$

- $\bar{t}_1, \bar{t}_2, \bar{t}_3 \geq 0$



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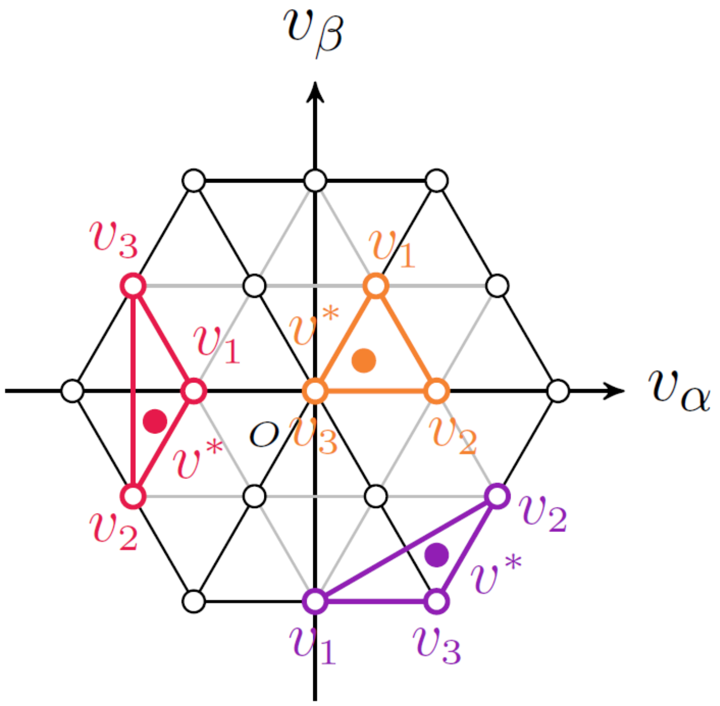
Proposed modulation method

- *Online adaptive* SVM

- Geometrically, *any* triangle (convex combination) containing v^* possible instead of the *closest* one

- The *voltage* and *current paths*

$$V^* = \begin{bmatrix} v_1^* \\ \vdots \\ v_L^* \end{bmatrix} \text{ and } I = \begin{bmatrix} i_1 \\ \vdots \\ i_L^* \end{bmatrix}$$



- The *'best'* triangle chosen that improves loss-THD trade-off

Proposed modulation method (cont'd)

- *Optimization* window L
- For each p-th modulation cycle T_s,

$$f_p = w_{loss,p}\left(\sum_{q=1}^{3}\sum_{r=a,b,c} E_{p,q,r}\right)^2 + w_{THD,p}\left(\sum_{q=1}^{3} e_{p,q,\alpha}^2 + e_{p,q,\beta}^2\right)$$

- Choose switching sequence which *minimizes* $f = \sum_{p=1}^{L} f_p$

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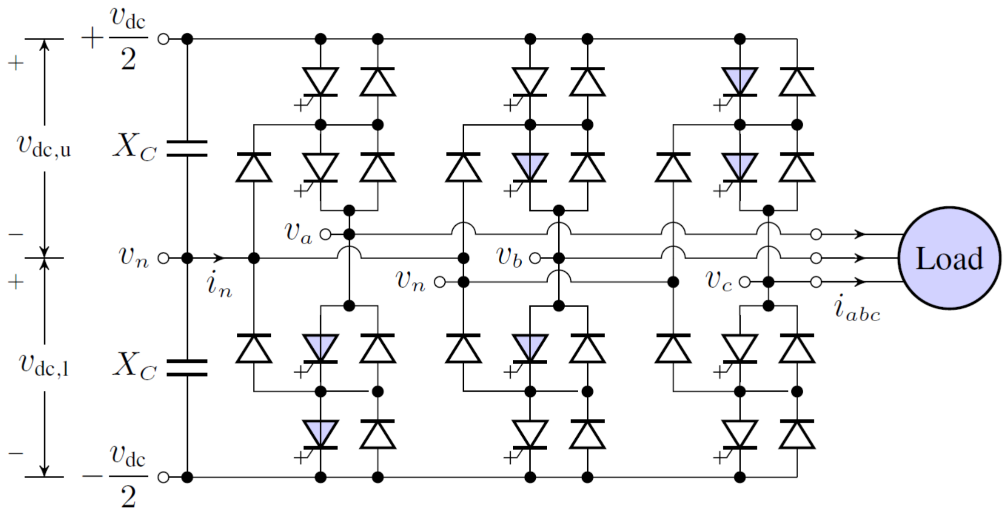
Neutral-point voltage balancing

- How does neutral-point *voltage* behave?

$$\frac{dv_n}{dt} = -\frac{1}{2X_C} i_n$$



- Neutral-point *current* drawn only if phase connected to neutral-point

$$i_n = (1 - |u_a|)i_a + (1 - |u_b|)i_b + (1 - |u_c|)i_c$$

- Predict using *forward Euler* $v_n(t + \Delta t) = v_n(t) + \Delta t \cdot -\frac{1}{2X_C} i_n$

Proposed modulation method (cont'd)

- *Optimization* window L

- For each p-th modulation cycle T_s,

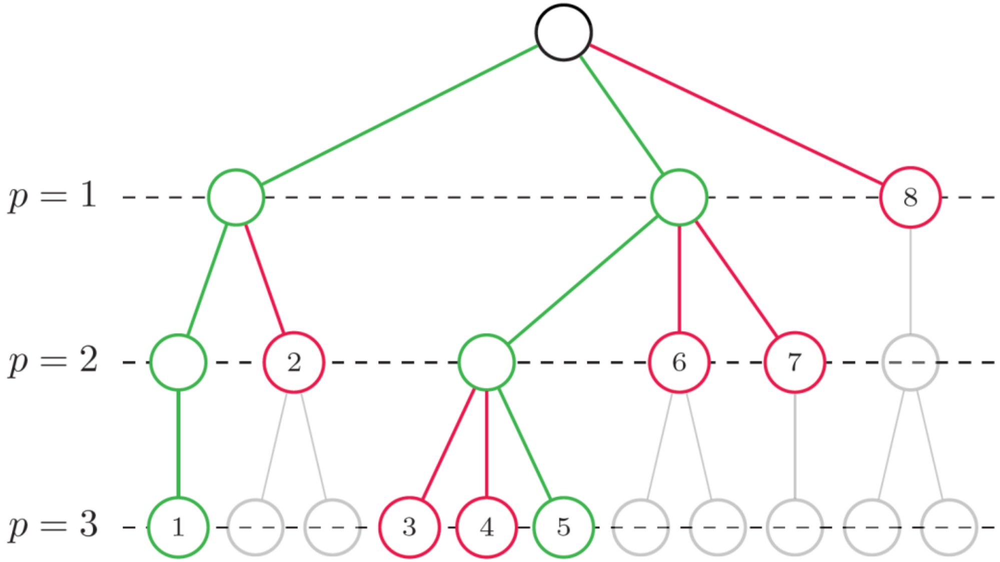
$$f_p = w_{loss,p}\left(\sum_{q=1}^{3}\sum_{r=a,b,c} E_{p,q,r}\right)^2 + w_{THD,p}\left(\sum_{q=1}^{3} e_{p,q,\alpha}^2 + e_{p,q,\beta}^2\right)$$
$$+ w_{v_n,p} v_{n,p}^2$$

- Choose switching sequence which *minimizes* $f = \sum_{p=1}^{L} f_p$

- Weights depend whether $v_{n,p}$ within *bounds*

Proposed modulation method (cont'd)

- *Integer* optimization problem
- $3L$ decision variables, each with 27 vectors, so 27^{3L} *possible combinations*
- Solved using *branch and bound* method
- Every *node* represents a triangle (3 vectors)



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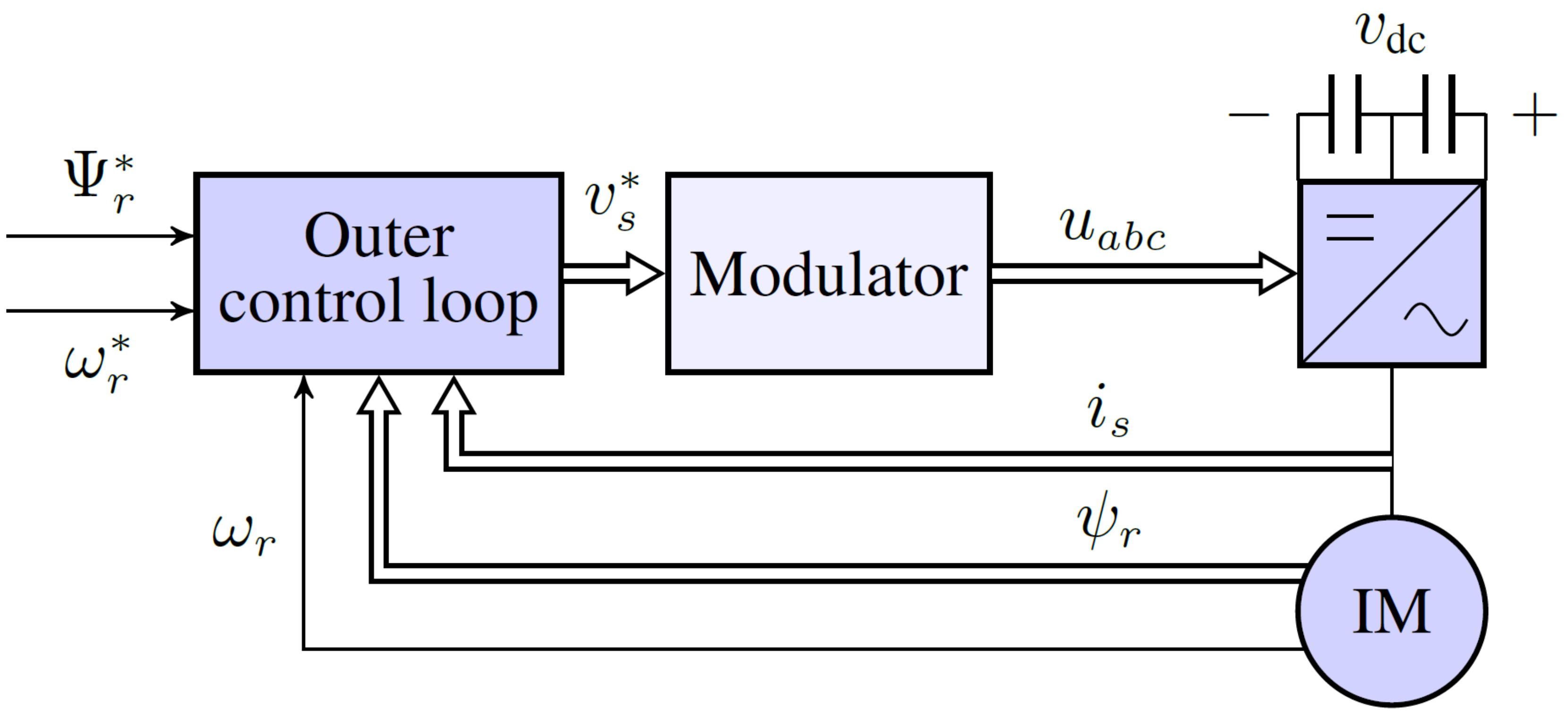
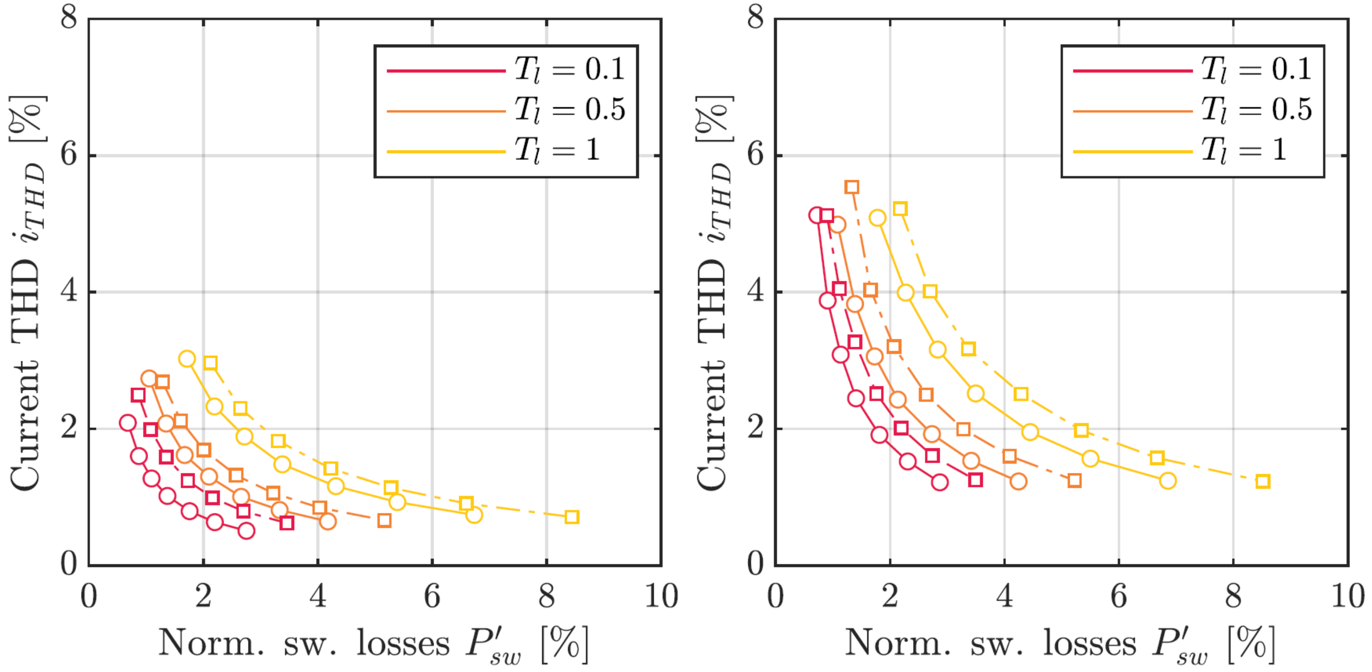
Field-oriented control



Loss-THD trade-off

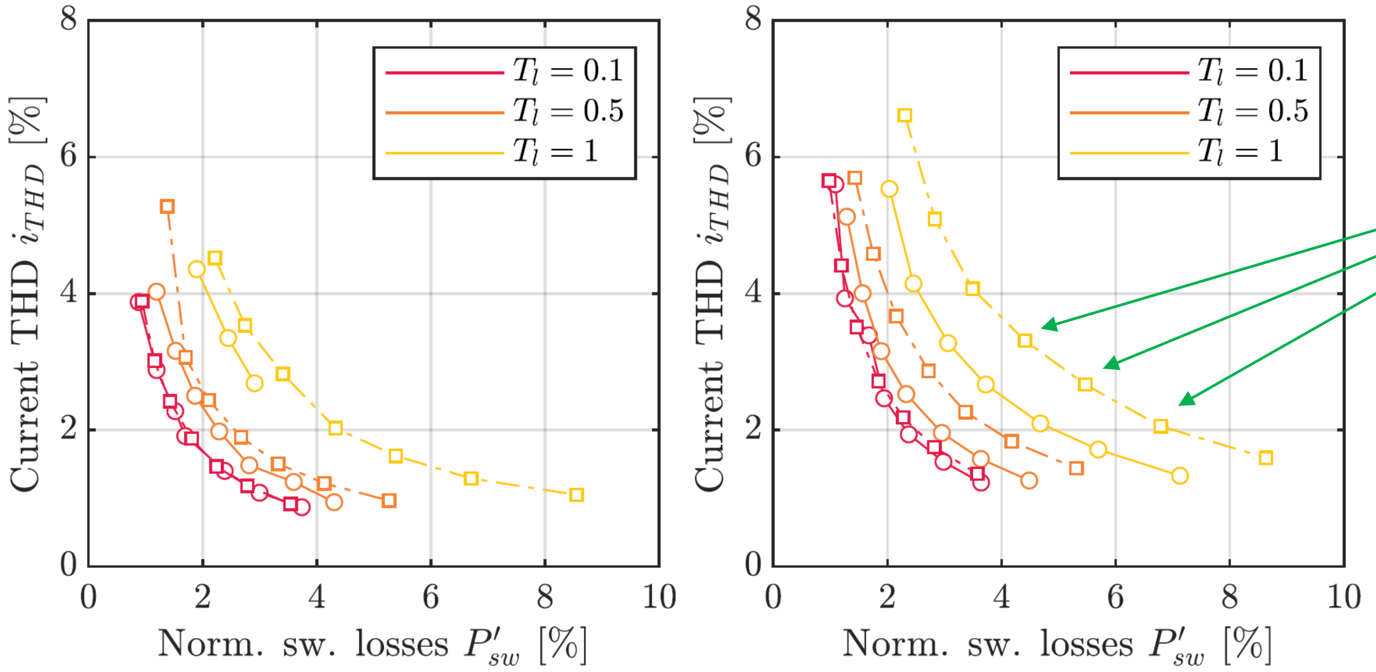
- *SVM* (dash-dotted squares) vs *oaSVM* (solid circles)
- For $L = 1$, *speed* $\omega_r = 0.1$ pu (left) and $\omega_r = 0.4$ pu (right),

Parameter	Value
w_{loss}	1
w_{THD}	320
w_{v_n}	$1 \cdot 10^9$
$v_{n,min}$	-0.04 pu
$v_{n,max}$	0.04 pu



Loss-THD trade-off (cont'd)

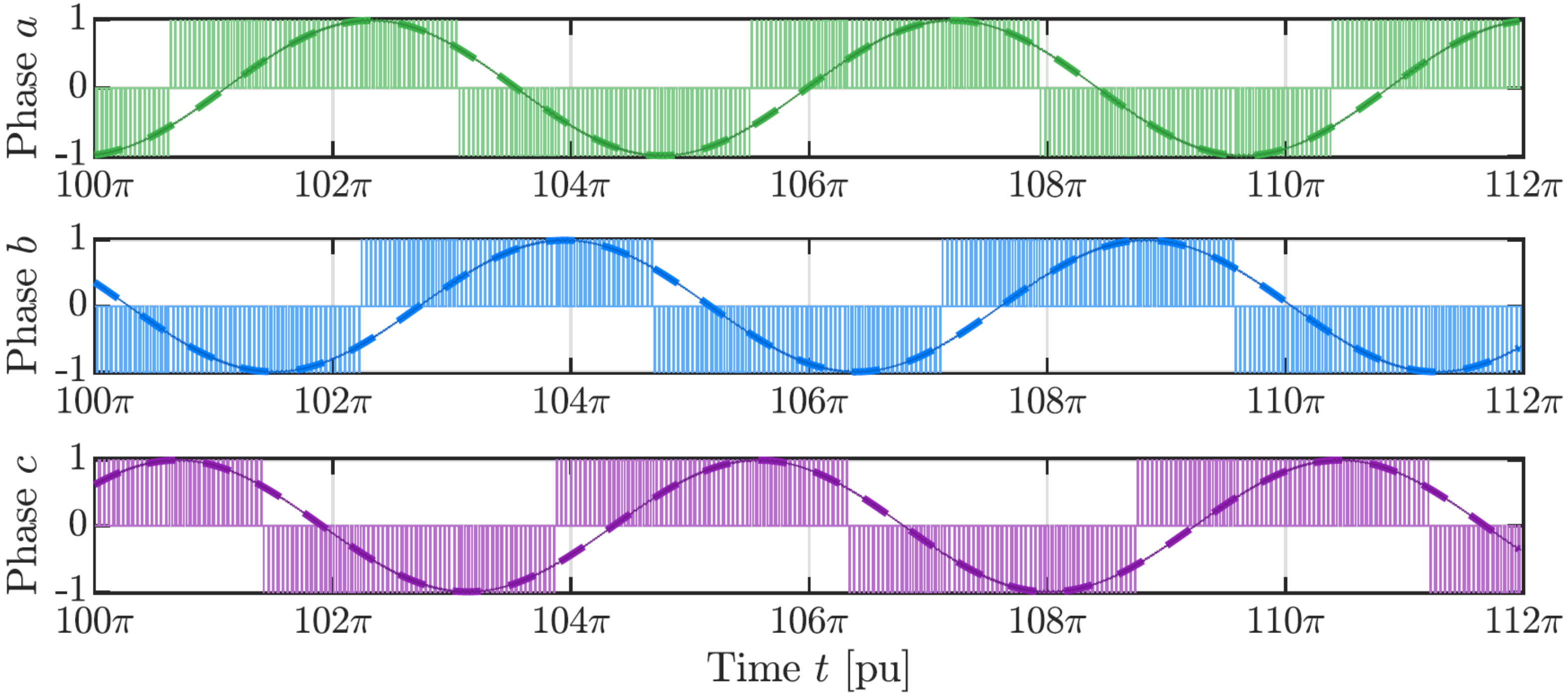
- *SVM* (dash-dotted squares) vs *oaSVM* (solid circles)
- For $L = 1$, *speed* $\omega_r = 0.7$ pu (left) and $\omega_r = 1$ pu (right)
- Same *parameters* as before
- *Infeasibility* solvable using longer optimization windows



Losses reduced by *29.5%* for same THD for $T_l = \omega_r = 1$ pu

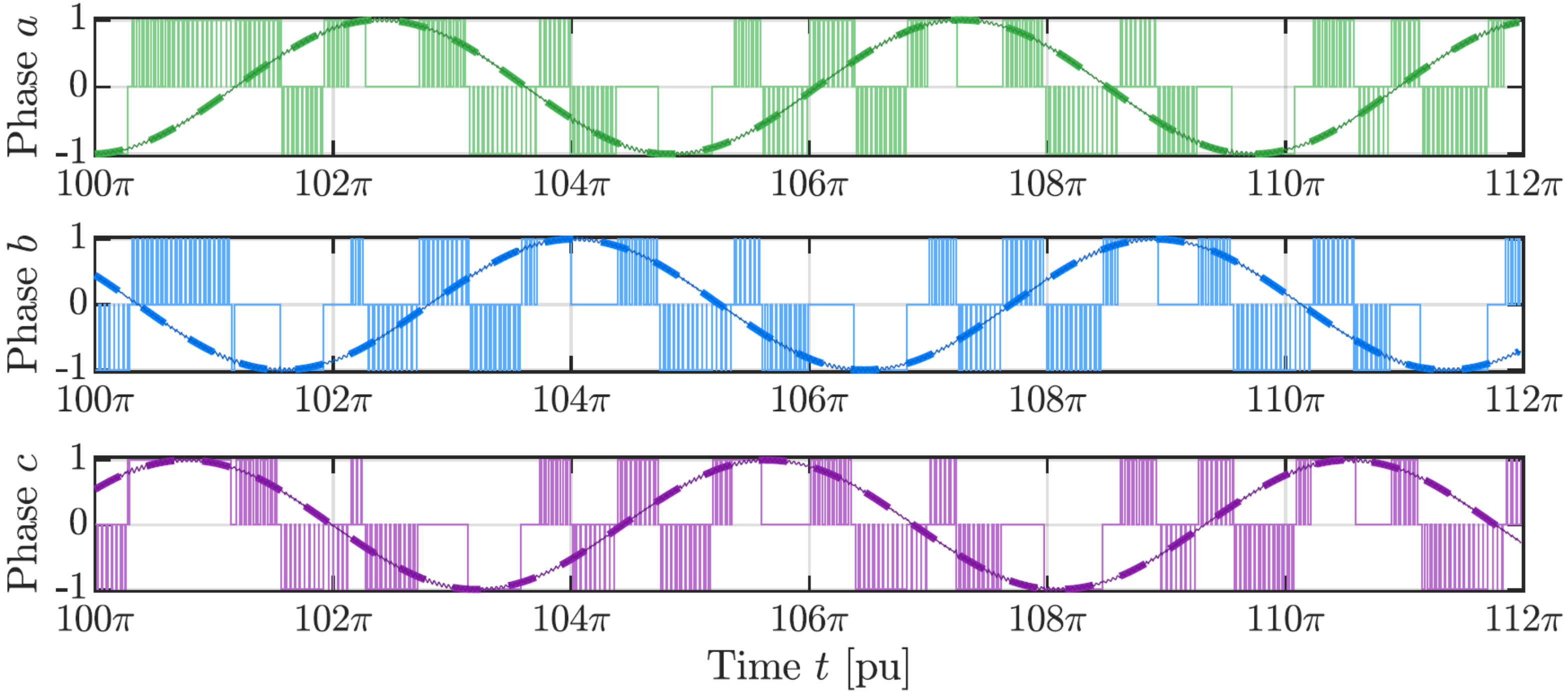
Space vector modulation

- For *speed* $\omega_r = 0.4$ pu, *load* $T_l = 1$ pu
- Same *parameters* as before



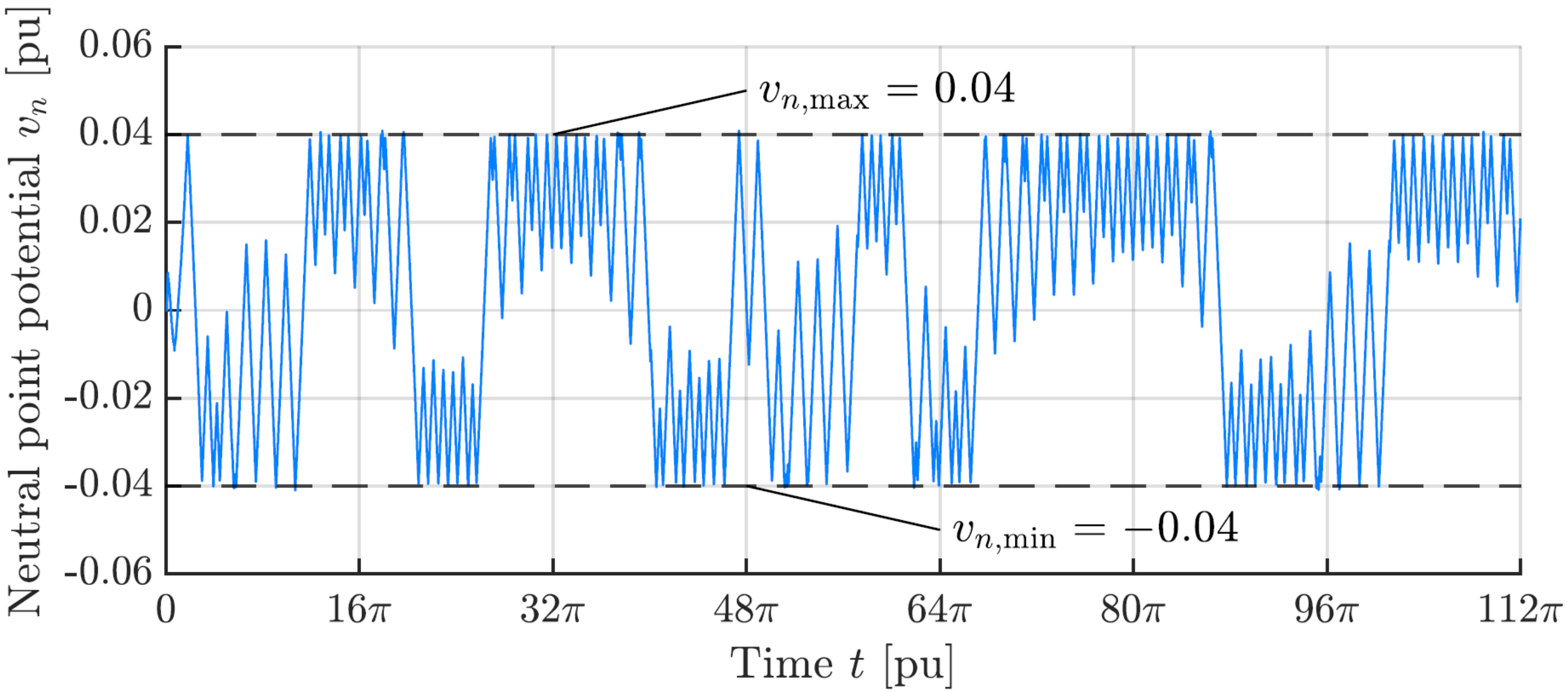
Online adaptive SVM

- For *speed* $\omega_r = 0.4$ pu, *load* $T_l = 1$ pu
- Same *parameters* as before
- *Clamps* at high currents, similar to discrete PWM



Online adaptive SVM (cont'd)

- For *speed* $\omega_r = 0.4$ pu, *load* $T_l = 1$ pu
- Same *parameters* as before



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Conclusion

Summary

- New modulation method *online adaptive SVM*
- Blend of *SVM* and discrete PWM, very flexible
- Improves *trade-off* between losses and THD
- Balances *neutral-point voltage* within bounds
- *Infeasibility* solvable for longer optimization windows
- High computational complexity, *brand and bound* method

Future work:

- Investigate longer *optimization window* $L > 1$
- Explore other *cost functions*

Thank you for your attention!

Contact info

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