Direct Power Control: Theories and Applications

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Key References

[1] S. Yan, Y. Yang, S. Y. Hui and F. Blaabjerg, "**A Review on Direct Power Control of Pulsewidth Modulation Converters**," in *IEEE Trans. on Power Electron.*, vol. 36, no. 10, pp. 11984-12007, Oct. 2021.

[2] S. Yan, J. Chen, M. Wang, Y. Yang and J. M. Rodriguez, "**A Survey on Model Predictive Control of DFIGs in Wind Energy Conversion Systems** ," in *IEEE Trans. on Power Electron. (under review).*

[3] S. Yan, et al, "**A General Space Vector Modulation Method of Three-Phase Multilevel Converters** ," in *IEEE Trans. on Power Electron. (under review).*

Acknowledgement

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Prof Kai Sun, Tsinghua University

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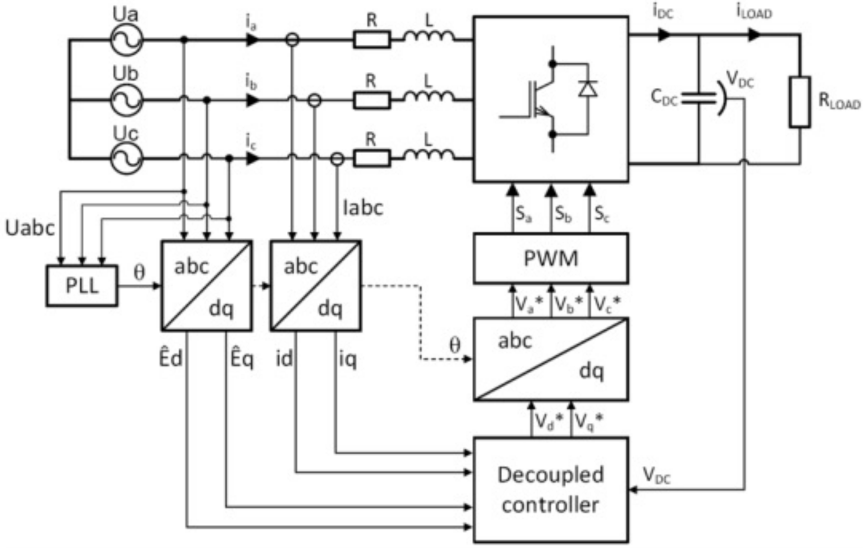
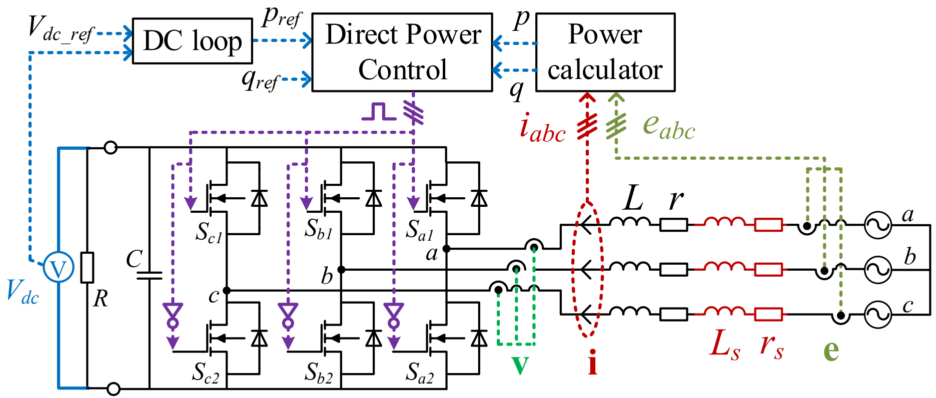
List of Content

Introduction

➢ **Voltage-Oriented Control (VOC)**



➢ **Direct Power Control (DPC)** [1]



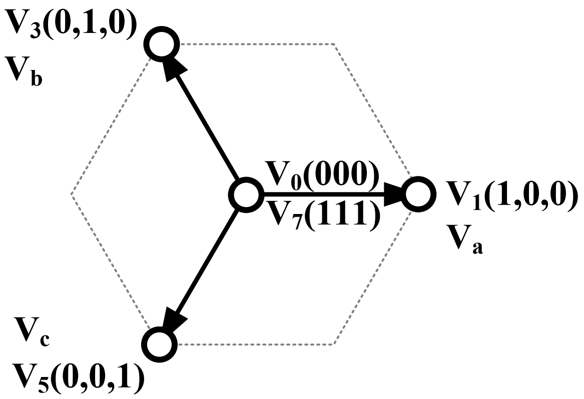
Introduction

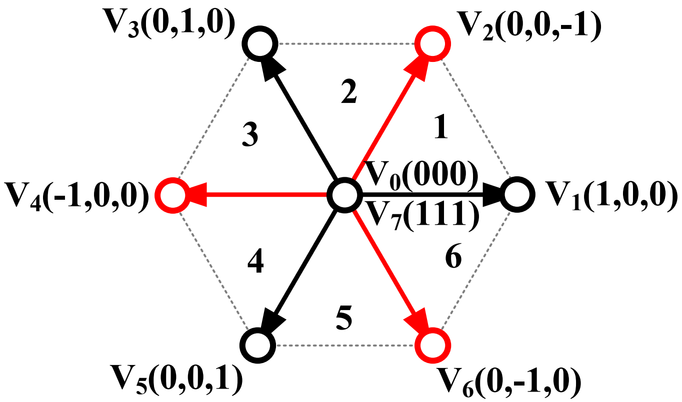
- **Comparison of Two Mainstream Controls** [1]

VOC	DPC
Average Model	Discrete Model
Frame Transformation (*d*-*q* or *α*-*β*)	Optional
Double Loops (Current and Voltage)	Single Loop or Nonlinear logics
Linear Controller (PI or PR)	Optional
Pulsewidth Modulation	Optional

Basics of DPC

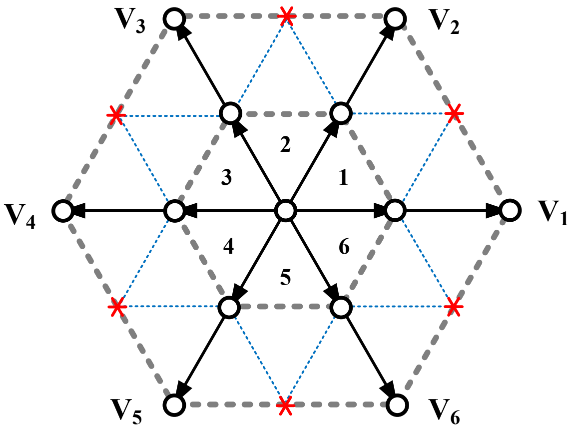
- **Space Vectors (2-Level Converters) [3]**

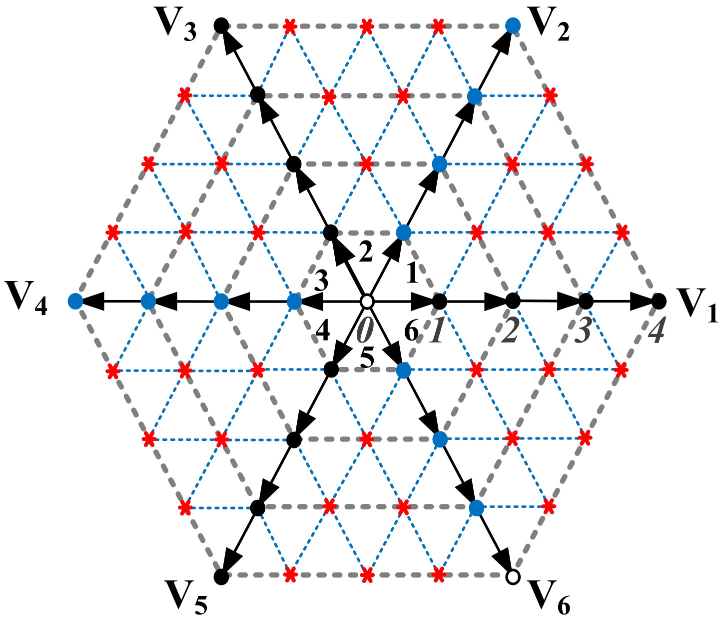




Basics of DPC

➢ **Space Vectors (n-Level Converters)** [3]





[3] S. Yan, et al, "**A General Space Vector Modulation Method of Three-Phase Multilevel Converters**," in *IEEE Trans. on Power Electron. (under review).*

Basics of DPC

- **Power Derivative and Space Vectors**

1. PWM converters

Instantaneous Power

$$\mathbf{S} = \frac{3}{2}\left(\mathbf{e} \cdot \mathbf{i}^{*}\right)$$

Basics of DPC

- **Power Derivative and Space Vectors**

1. PWM converters

Instantaneous Power

$$\mathbf{S} = \frac{3}{2}\left(\mathbf{e}\cdot\mathbf{i}^*\right)$$

Full differentiation

$$\frac{d\mathbf{S}}{dt} = \frac{3}{2}\left(\boxed{\frac{d\mathbf{e}}{dt}}\cdot\mathbf{i}^* + \mathbf{e}\cdot\boxed{\frac{d\mathbf{i}^*}{dt}}\right)$$

Voltage derivative $\frac{d\mathbf{e}}{dt} = j\omega\mathbf{e}$

Current derivative $\frac{d\mathbf{i}}{dt} = \frac{1}{L}\left(\mathbf{e} - \mathbf{v} - r\mathbf{i}\right)$

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Basics of DPC

➢ **Power Derivative and Space Vectors**

1. PWM converters

Instantaneous Power

$$\mathbf{S} = \frac{3}{2}\left(\mathbf{e}\cdot\mathbf{i}^*\right)$$

Full differentiation

$$\frac{d\mathbf{S}}{dt} = \frac{3}{2}\left(\boxed{\frac{d\mathbf{e}}{dt}}\cdot\mathbf{i}^* + \mathbf{e}\cdot\boxed{\frac{d\mathbf{i}^*}{dt}}\right)$$

Voltage derivative $\frac{d\mathbf{e}}{dt} = j\omega\mathbf{e}$

Current derivative $\frac{d\mathbf{i}}{dt} = \frac{1}{L}\left(\mathbf{e} - \mathbf{v} - r\mathbf{i}\right)$

$$\frac{d\mathbf{S}}{dt} = \frac{3}{2L}\left(E^2 - \mathbf{e}\cdot\mathbf{v}^*\right) - \frac{1}{L}\left(r - j\omega L\right)\cdot\mathbf{S}$$

Basics of DPC

➢ **Power Derivative and Space Vectors**

1. PWM converters

$$\frac{d\mathbf{S}}{dt}=\frac{3}{2L}\left(E^2-\mathbf{e}\cdot\mathbf{v}^*\right)-\frac{1}{L}\left(r-j\omega L\right)\cdot\mathbf{S}$$

Actuator: **v** → Core DPC Methods

Feedback: ***e, S*** → Sensorless DPCs

Uncertainty: *L, r* → Robust DPCs

Basics of DPC

➢ Power Derivative and Space Vectors

2. DFIG

Instantaneous Power

$$\mathbf{S} = \frac{3}{2}\left(\mathbf{v}_s \cdot \mathbf{i}_s^*\right)$$

Full differentiation

$$\frac{d\mathbf{S}}{dt} = \frac{3}{2}\left(\mathbf{v}_s \cdot \boxed{\frac{d\mathbf{i}_s^*}{dt}} + \boxed{\frac{d\mathbf{v}_s}{dt}} \cdot \mathbf{i}_s^*\right)$$

Stator Voltage derivative

Stator Current derivative

$$\frac{d}{dt}\mathbf{i}_s = -\left(\lambda L_r R_s + j\omega_{sl}\right)\mathbf{i}_s + \lambda L_m R_r \mathbf{i}_r$$
$$+ j\lambda\left(-\omega_s L_s + \omega_{sl} L_r\right)\boldsymbol{\psi}_s + \lambda L_r \mathbf{v}_s - \lambda L_m \mathbf{v}_r$$

Feedback: $\boldsymbol{i_s}$ $\boldsymbol{i_r}$ $\boldsymbol{v_s}$

Observations: ψ_s

Uncertainty: L_m

Actuator: $\boldsymbol{v_r}$

Basics of DPC

The Use of Power Derivative

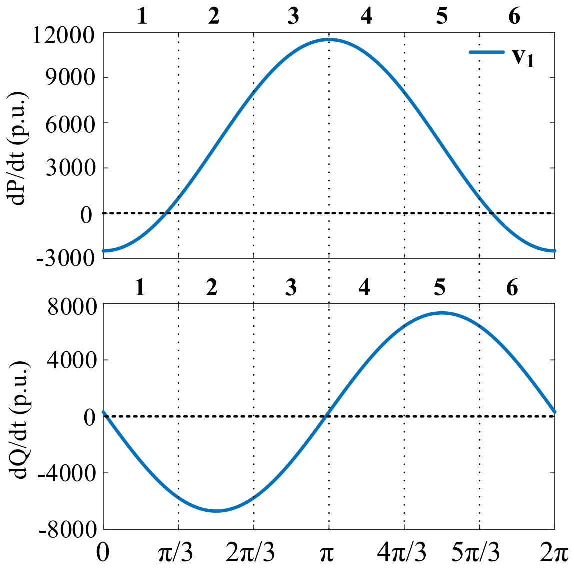
$$\frac{d\mathbf{S}}{dt} = f(\mathbf{v})$$

- Derivative plots
- One-step (or multi-step) prediction
- Discretize + Inverse calculation
- Linear control
- Sliding mode model control
- Robust model-free control

Table-Based DPCs

- **The Iteration of Power Derivative**

$$\frac{d\mathbf{S}}{dt} = f(\mathbf{v}) \longrightarrow \text{Iterations: } \frac{d\mathbf{S}}{dt} = f(\mathbf{v}_i), i = 1, 2 \cdots, n$$



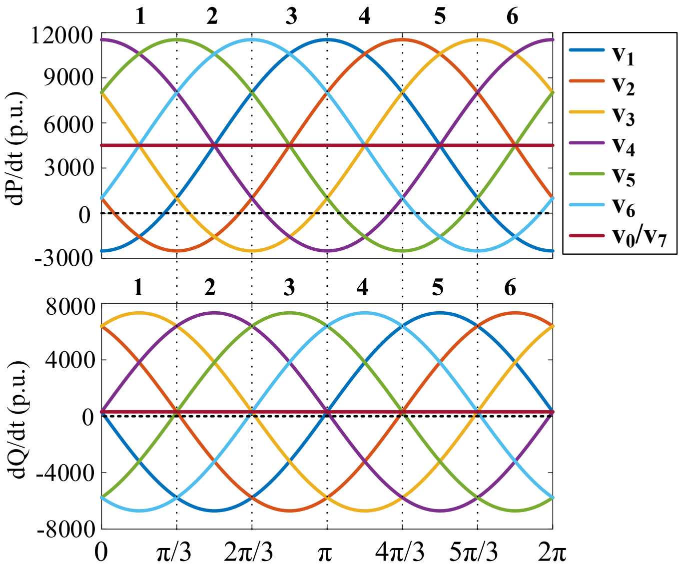


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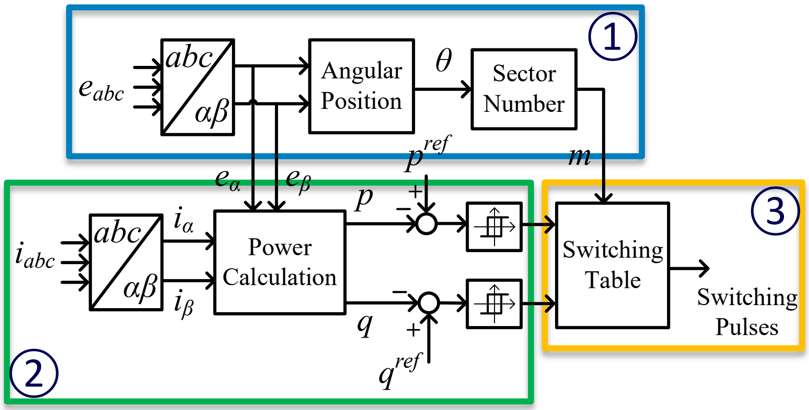
Table-Based DPCs

➢ **Control Formation**

p	q	The Sector Number					
		1	2	3	4	5	6
↑	↑	V4	V5	V6	V1	V2	V3
↑	↓	V6	V1	V2	V3	V4	V5
↓	↑	V2	V3	V4	V5	V6	V1
↓	↓	V1	V2	V3	V4	V5	V6

(One example)

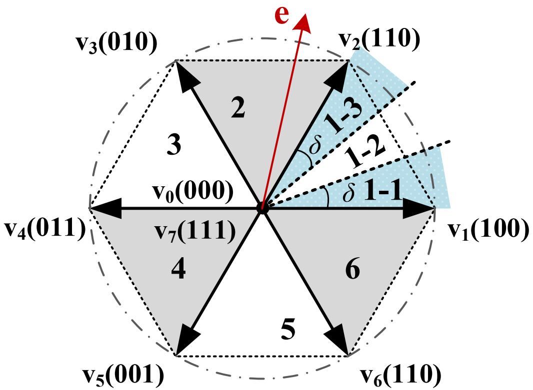


1. Angle Calculator
2. Power Error Calculator
3. Switching Table

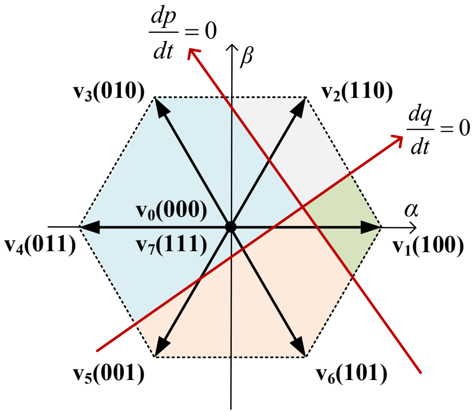
Table-Based DPCs

➢ **Improvements (Accuracy and Ripple Reduction) [1]**

- Vector redundance
- Sector refinement



- Output Regulation Subspace Analysis

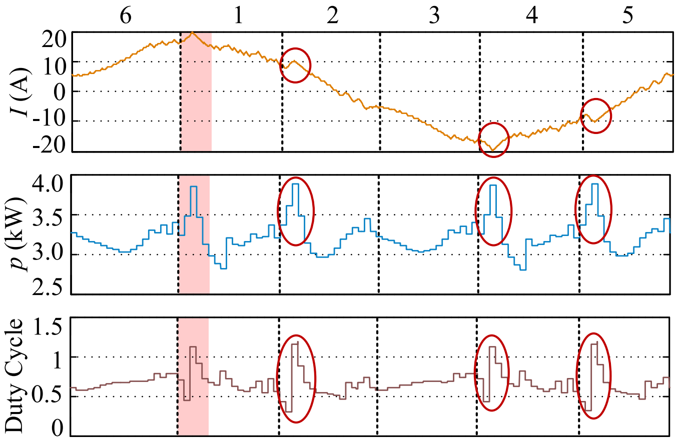


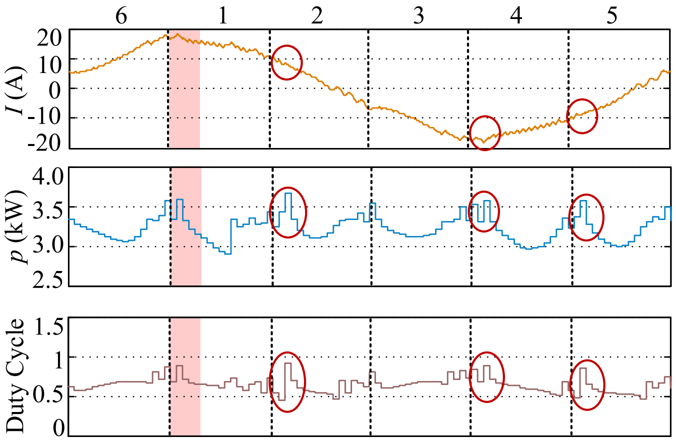
- Dynamic table

Table-Based DPCs

➢ **Improvements (Accuracy and Ripple Reduction) [1]**

- Removal of false duty cycles[4]





[4] S. Yan, J. Chen, T. Yang, and S. Y. Hui, "**Improving the Performance of Direct Power Control Using Duty Cycle Optimization**," *IEEE Trans. Power Electron.,* vol. 34, no. 9, pp. 9213-9223, Sept. 2019.

Predictive DPCs

- **Finite-Control-Set Predictive DPC (FCS-P-DPC)**

$$\frac{d\mathbf{S}}{dt} = f(\mathbf{v}) \longrightarrow$$

Prediction: $$\mathbf{S}_i(k+1) = \mathbf{S}(k) + T_s \cdot \left.\frac{d\mathbf{S}}{dt}\right|_{\mathbf{v}_i}, i = 1, 2, \cdots n$$

Objective Function: $$obj = \left\| \mathbf{S}_{ref} - \mathbf{S}_i(k+1) \right\|_m^m$$

Optimization: $$\mathbf{v}_{opt} = \min(obj)$$

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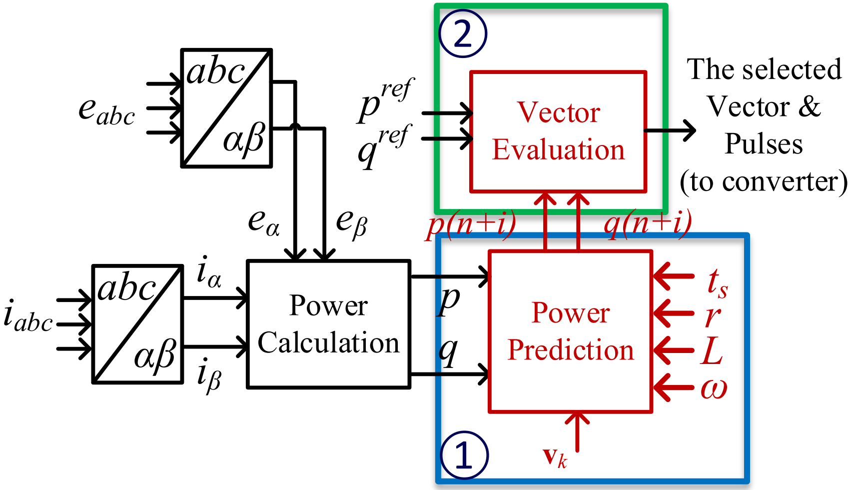
Predictive DPCs

- **Single-Vector FCS-P-DPC**



1. Power error prediction:
   power derivative, power prediction, error calculation
2. The selection of the optimal vector

Predictive DPCs

Multi-Vector FCS-P-DPC

1. Duty cycle calculation

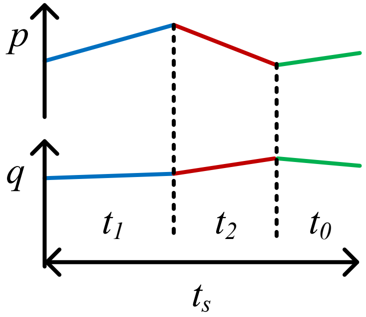
$$\mathbf{y}(k+1)=\mathbf{y}(k)+\sum_{j=1}^{h}\left(\left.\frac{d\mathbf{y}(t)}{dt}\right|_{u(l)_j}\cdot t_j\right)$$

$$\mathbf{e}(k+1)=\mathbf{y}^{ref}(k+1)-\mathbf{y}(k+1)$$

$$\begin{cases}\dfrac{\partial\mathbf{e}(k+1)}{\partial t_1}=0\\ \quad\cdots\\ \dfrac{\partial\mathbf{e}(k+1)}{\partial t_h}=0\end{cases}$$

subject to: $\sum_{j=1}^{h}t_j=T_s$

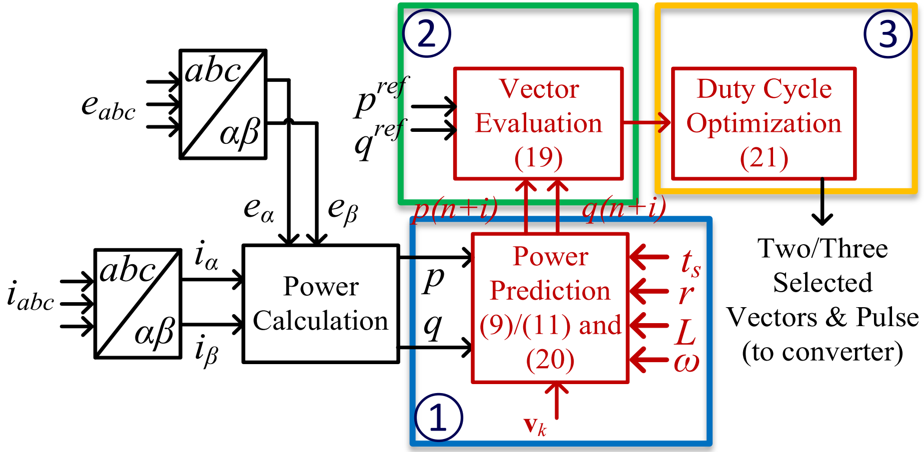
2. An example of three-vector's approach



Predictive DPCs

- **Multi-Vector FCS-P-DPC**

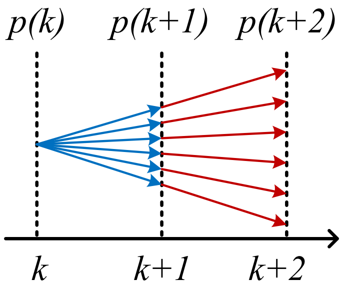
3. Control Formation



1. Power error prediction: power derivative, power prediction, error calculation
2. The selection of the optimal vectors
3. Duty cycle calculation

Predictive DPCs

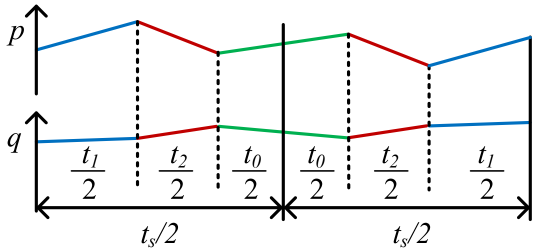
- **FCS-P-DPC Improvements (Accuracy and Ripple Reduction)** [1]
  - Two-vector approaches: Active plus zero, two active vectors
  - Two-step prediction



Predictive DPCs

➢ **FCS-P-DPC Improvements (Accuracy and Ripple Reduction)[1]**

- Three-vector approaches: 3+3



- Low-complexity evaluation: negative conjugate of complex power

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Predictive DPC

- **Deadbeat P-DPC**

$$\frac{d\mathbf{S}}{dt} = f(\mathbf{v})$$

Discretization: $$\frac{\mathbf{S}(n+1)-\mathbf{S}(n)}{T_s} = f(\mathbf{v})$$

Inverse Function: $$\mathbf{v} = f^{-1}\left(\frac{\mathbf{S}(n+1)-\mathbf{S}(n)}{T_s}\right)$$

Absolute Solution: $$\mathbf{v}_{ref} = f^{-1}\left(\frac{\mathbf{S}_{ref}-\mathbf{S}(n)}{T_s}\right)$$

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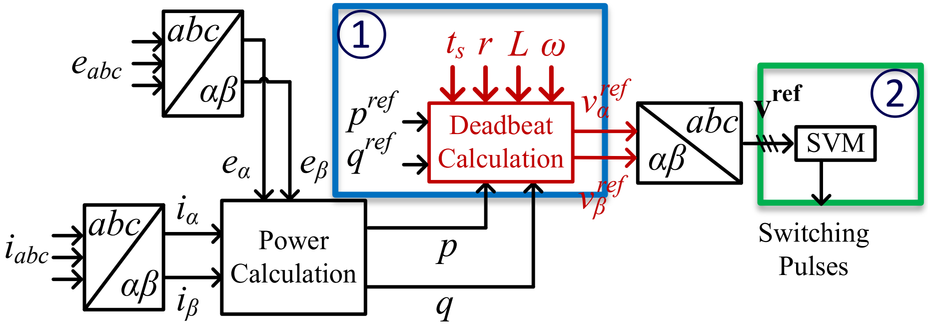
Predictive DPCs

- **Deadbeat P-DPC**



1. Deadbeat calculation: Inverse function
2. Space vector modulation

Predictive DPCs

➢ Deadbeat P-DPC Improvements: Robustness[1]

- Influence of Inductance Variation

$\tilde{L} < L$ → Worsened current quality and power error

$\tilde{L} > L$ → Worsened current quality

Solutions:

1. Ohm' theory
2. Constant voltage magnitude
3. Continuity of line current and DC voltage
4. Least-square evaluation

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Predictive DPCs

➢ **Implementation Issues**

- Sampling delay

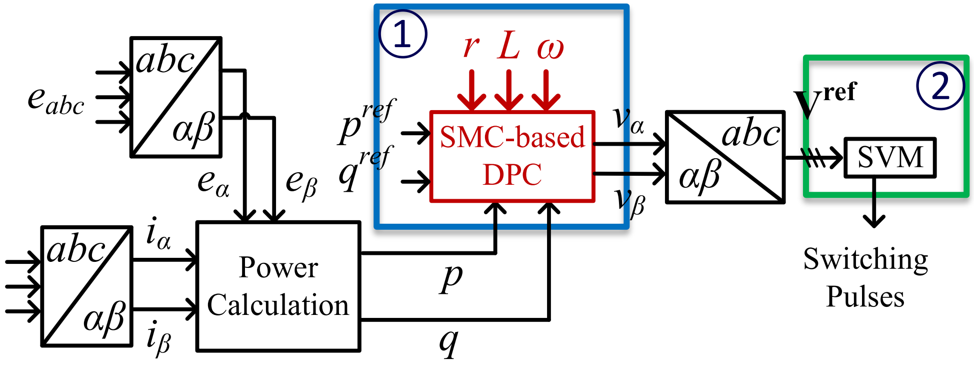
  Two-step prediction;
  Incorporation of delay in the discrete model
  Observer-based methods

- Objective functions

  l_1-norm, l_2-norm, or others;
  Additional control constraints;
  Weighting factors (weight-factor-less methods)

Other Nonlinear DPCs

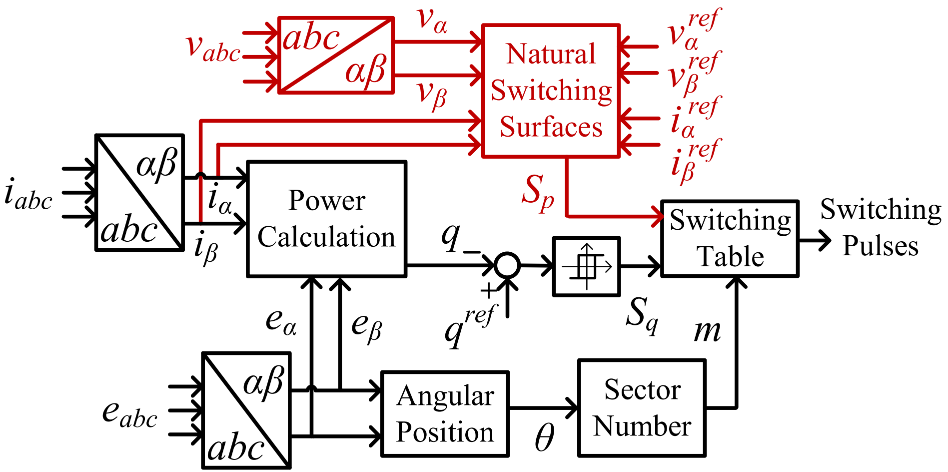
➢ **Sliding Mode DPCs**



1. Sliding mode algorithm: equivalent function
2. Space vector modulation

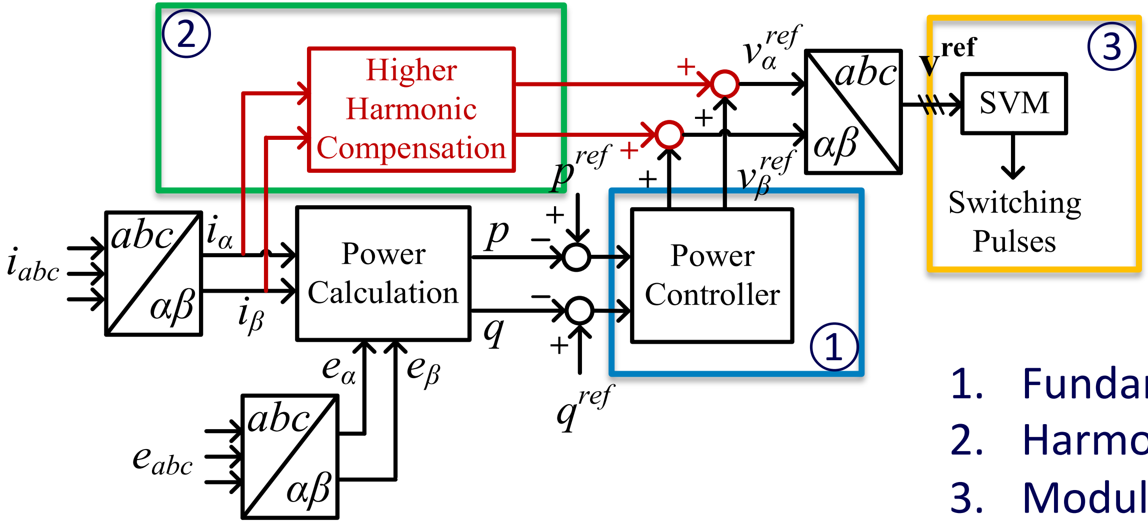
Other Nonlinear DPCs

- **Super Twisting DPCs**



DPC with Linear Controllers

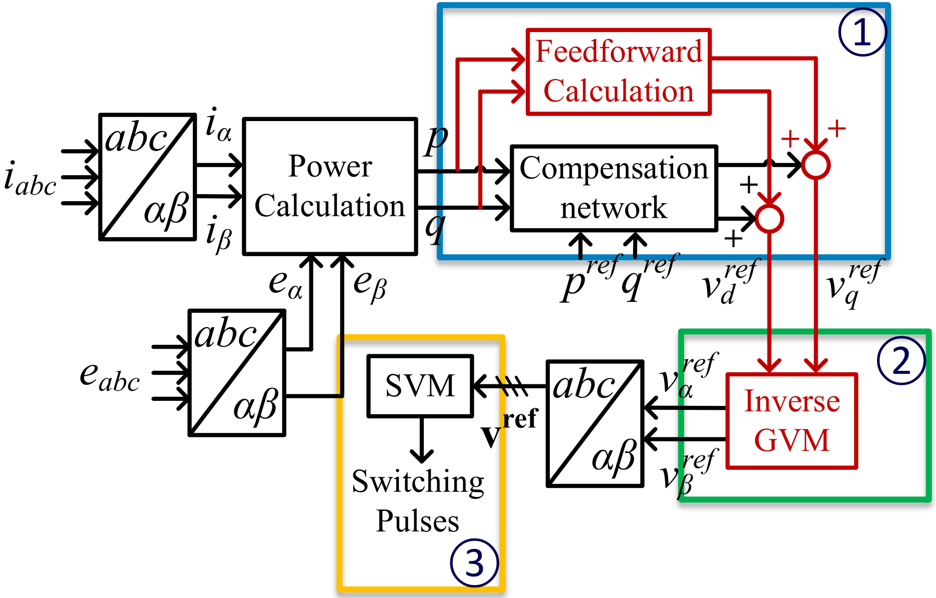
- **α-β frame**



1. Fundamental Freq PR controller
2. Harmonic PR controller
3. Modulation

DPC with Linear Controllers

- **d-q frame**[5]



1. Linear controller and cancellation terms
2. Inverse Clarke transformation
3. Modulation

[5] Y. Gui, et el, "**Improved Direct Power Control for Grid-Connected Voltage Source Converters**," *IEEE Trans. Ind. Electron.*, vol. 65, no. 10, pp. 8041-8051, Oct. 2018.

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Sensorless DPCs

- **Source Voltage Estimation**

$$\frac{d\mathbf{i}}{dt} = \frac{1}{L}\left(\mathbf{e} - \mathbf{v} - r\mathbf{i}\right) \Rightarrow \mathbf{e} = \mathbf{v} + r\mathbf{i} + L\frac{d\mathbf{i}}{dt}$$

- **Virtual Flux and More**

$$\mathbf{e} = \mathbf{v} + r\mathbf{i} + L\frac{d\mathbf{i}}{dt} \Rightarrow \int \mathbf{e} = \int\left(\mathbf{v} + r\mathbf{i} + L\frac{d\mathbf{i}}{dt}\right) \Rightarrow \boldsymbol{\psi} = \int \mathbf{v} + L\mathbf{i}$$

Sensorless DPCs

- **Source Voltage Estimation**

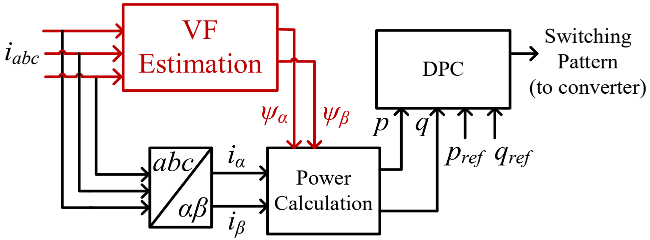
$$\frac{d\mathbf{i}}{dt} = \frac{1}{L}\left(\mathbf{e} - \mathbf{v} - r\mathbf{i}\right) \Rightarrow \mathbf{e} = \mathbf{v}(k) + r\mathbf{i} + L\frac{\mathbf{i}(k) - \mathbf{i}(k-1)}{t_s}$$

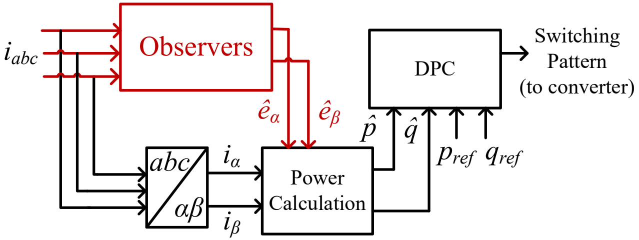
- **Virtual Flux and More**

$$\mathbf{e} = \mathbf{v} + r\mathbf{i} + L\frac{d\mathbf{i}}{dt} \Rightarrow \int \mathbf{e} = \int\left(\mathbf{v} + r\mathbf{i} + L\frac{d\mathbf{i}}{dt}\right) \Rightarrow \boldsymbol{\psi} = \int \mathbf{v} + L\mathbf{i}$$

Sensorless DPCs

➢ Virtual Flux and More





1. Issues of pure integrators: dc drifting and saturation
2. Improvements:
   Frequency-adaptive integrators
   First-order low pass filters (FOLP)
   Second-order general integrators (SOGI)
   Observer-based estimator: SMO, LO, Kalman filter.

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Unbalanced Operation of DPCs

- Revisit of Instantaneous Power Theory

$$\mathbf{e} = \mathbf{e}^{+} + \mathbf{e}^{-} = E^{+}e^{j\omega t} + E^{-}e^{-j\omega t}$$

$$\mathbf{S} = \frac{3}{2}\left(\mathbf{e}\cdot\mathbf{i}^{*}\right)$$

$$\mathbf{i} = \mathbf{i}^{+} + \mathbf{i}^{-} = I^{+}e^{j\omega t} + I^{-}e^{-j\omega t}$$

$$\begin{cases} p = P_0 + P_{c2}\cos\left(2\omega t\right) + P_{s2}\sin(2\omega t) \\ q = Q_0 + Q_{c2}\cos\left(2\omega t\right) + Q_{s2}\sin(2\omega t) \end{cases}$$

6 power terms with 4 variables.

Unbalanced Operation of DPCs

➢ **Extended Power Definitions**

$$\boxed{\mathbf{e}' = E^{+} e^{j(\omega t \text{-} 90^\circ)} + E^{-} e^{-j(\omega t \text{-} 90^\circ)}}$$

$$P_s^{ext} = -\frac{3}{2}\operatorname{Im}\left(\mathbf{i}^{*} \cdot \mathbf{e}'\right)$$

$$Q_s^{ext} = \frac{3}{2}\operatorname{Re}\left(\mathbf{i}^{*} \cdot \mathbf{e}'\right)$$

$$\begin{cases} p^{ext} = P_0^{ext} + P_{s2}^{ext}\sin\left(2\omega t\right) + P_{c2}^{ext}\cos\left(2\omega t\right) \\ q = Q_0 + Q_{c2}\cos\left(2\omega t\right) + Q_{s2}\sin(2\omega t) \end{cases}$$

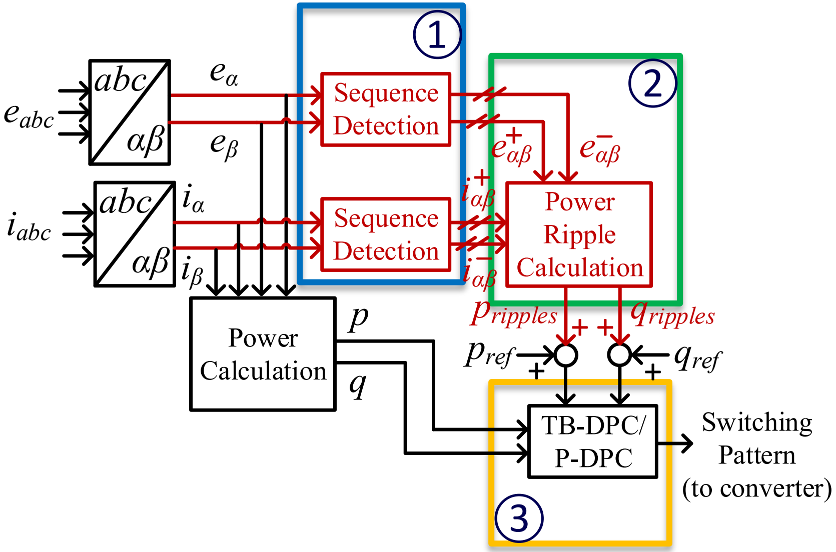
$$\begin{cases} q^{ext} = Q_0^{ext} + Q_{s2}^{ext}\sin\left(2\omega t\right) + Q_{c2}^{ext}\cos\left(2\omega t\right) \\ p = P_0 + P_{c2}\cos\left(2\omega t\right) + P_{s2}\sin(2\omega t) \end{cases}$$

$$\boxed{P_{c2}^{ext} = Q_{s2} \quad P_{s2}^{ext} = -Q_{c2}}$$

$$\boxed{Q_{s2}^{ext} = P_{c2} \quad Q_{c2}^{ext} = -P_{s2}}$$

Unbalanced Operation of DPCs

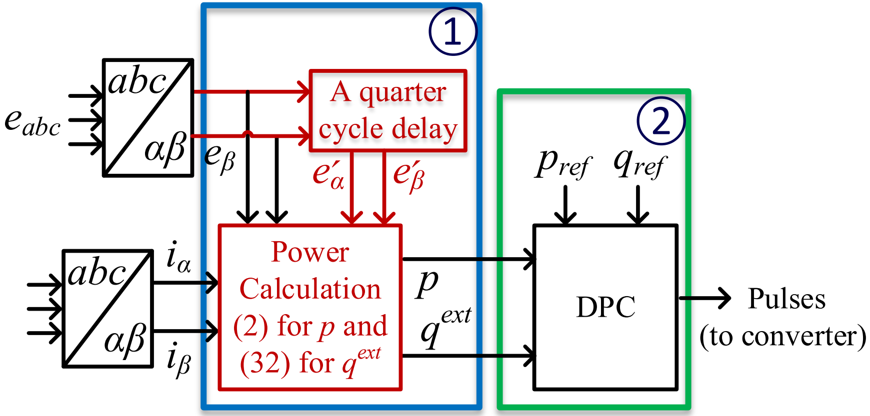
- **Power Ripple Compensation (classic definition)**



1. Sequence detection;
2. Ripple calculation, selective control targets;
3. DPC strategies.

Unbalanced Operation of DPCs

➢ **Power Ripple Compensation (extended definition)**



1. Extended power calculation;
2. DPC strategies.

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Mainstream Applications

- **PWM Converters**

TB-DPC
- Basic Tables
- Duty cycle calculation
- Fine vector selection

Linear DPC
- Decoupled power control
- PR control for harmonic compensation
- Grid voltage modulated DPC

P-DPC
- Single vector FCS-P-DPC
- Multi-vector FCS-P-DPC
- Deadbeat P-DPC
- Sampling delay compensation
- Objective functions
- Parameter estimation

Nonlinear-DPC
- Sliding mode control
- Backstepping control
- Supertwisting control
- Fuzzy logic control
- …

VF-DPC
- Pure integrators
- SOGI
- FOLP filters
- Observers

Unbalanced
- Selective control objectives
- Extended power
- Decoupled PI control
- PR control

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Mainstream Applications

➢ **Doubly Fed Induction Generators**

TB-DPC

- Basic Tables
- Duty cycle calculation
- Fine vector selection
  - Sector
  - Vector

Linear DPC

- Decoupled power control
- PR control for harmonic compensation
- Grid voltage modulated (GVM) DPC

P-DPC

- Single vector FCS-P-DPC
- Multi-vector FCS-P-DPC
- Deadbeat P-DPC
- Sampling delay compensation
- Objective functions
- Parameter estimation

Nonlinear-DPC

- Sliding mode control
- Backstepping control
- Supertwisting control
- Fuzzy logic control
- …

Unbalanced

- Selective control objectives
- Extended power
- Decoupled PI control
- PR control

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Mainstream Applications

- Multilevel Converters
- Active Power Filters
- Single-Phase Converters

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