

Write a comprehensive, detailed summary with beautiful formatting, with all the formulas

Certainly! Below is a comprehensive and detailed summary of the book *Advanced Control Methodologies For Power Converter Systems*, covering key control strategies, mathematical formulations, control designs, and experimental validations for various power converter systems. The summary includes important formulas and highlights from each chapter, organized for clarity and depth.

Summary of *Advanced Control Methodologies For Power Converter Systems*

1. Introduction to Power Electronic Converters and Control Methods

Power electronic converters are essential components in modern power systems, enabling energy conversion between AC and DC forms and integrating renewable energy sources and storage devices. The control of these converters is critical for ensuring system stability, efficiency, and robustness [[1]].

1.1 Power Electronic Converters

- **Topology and Operation:** Power converters consist of power switches (e.g., IGBT), controllers, modulators, and drive circuits. The controller processes measurement signals to generate suitable control signals, which modulate the switches to achieve desired voltage and current waveforms (Fig. 1.1) [[1]].

1.2 Control Methods

Control methods are categorized into:

- **Linear Control Methods:** Proportional-Integral-Derivative (PID) controllers, mainly PI in (d, q) frame, and Proportional-Resonant (PR) controllers in (α , β) frame.

– *PI Controller Transfer Function:*

$$G_{PI}^{dq}(s) = k_p + \frac{k_i}{s}$$

– *PR Controller Transfer Function:*

$$G_{PR}^{\alpha\beta}(s) = k_p + \frac{k_i s}{s^2 + \omega^2}$$

- **Nonlinear Control Methods:** Including Sliding Mode Control (SMC), Adaptive Control, Fuzzy Logic Control, Model Predictive Control (MPC), and Neural Network Control.
 - **Disturbance Rejection Control Methods:** Based on disturbance observers and Active Disturbance Rejection Control (ADRC) techniques, where unknown disturbances are estimated and compensated in real-time (Fig. 1.13, 1.14).
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Part I: Disturbance Observer Based Control Methods

Chapter 2: Sliding Mode Control of Three-Phase Two-Level Converters

- **System Model:** The converter is modeled in (a, b, c), (,), and synchronous (d, q) frames as:

$$L \frac{d\mathbf{i}_{dq}}{dt} = -r\mathbf{i}_{dq} + \omega L \mathbf{J} \mathbf{i}_{dq} + \mathbf{v}_{dq} - \frac{V_{dc}}{L} \mathbf{u}_{dq}$$

$$C \frac{dV_{dc}}{dt} = \mathbf{u}_{dq}^T \mathbf{i}_{dq} - i_{load}$$

- **Control Objectives:**

- Regulate DC-link voltage

$$V_{dc} \rightarrow V_{dc}^*$$

- Track active

$$p$$

and reactive

$$q$$

power (or corresponding currents)

- **Control Scheme:** Voltage-oriented control (VOC) with two cascaded loops:
 - Outer voltage regulation loop: Super-twisting SMC compensated by disturbance observer.
 - Inner current tracking loop: Two super-twisting SMC controllers for d and q axis currents.
- **Disturbance Observers Compared:**
 1. Linear Disturbance Observer (LDO)
 2. Second-Order Sliding Mode Observer (SMO)

3. Linear Extended State Observer (LESO)
4. Nonlinear Extended State Observer (NESO)

- **Key Voltage Regulation Loop Equation:**

$$C \frac{dz_1}{dt} = \mu_{dc} - d$$

where

$$z_1 = \frac{V_{dc}^2}{2}$$

,

$$\mu_{dc}$$

is control input, and

$$d$$

is load disturbance.

- **Super-Twisting Controller:**

$$\mu_{dc} = \lambda_{vdc} |e_v|^{1/2} \text{sign}(e_v) + \alpha_{vdc} \int_0^t \text{sign}(e_v) d\tau$$

- **Simulation Results:** Second-order SMO showed superior disturbance rejection with smaller voltage dip and faster recovery [[2]].

Chapter 3: Proportional-Integral Control of Three-Phase Two-Level Converters

- **Improved Linear Disturbance Observer (LDO)** designed with two parameters

$$\beta$$

and

$$K_{ldo}$$

to improve transient response without deteriorating steady-state current THD.

- **Observer Design:**

$$C \dot{\hat{z}} = K_{ldo}(u + \beta \hat{e}_z), \quad \hat{e}_z = z - \hat{z}$$

- **Closed-loop System Equation:**

$$\dot{x} = Ax + Bd$$

where

$$x = [\int e_z dt, e_z, e_d]^T$$

and

$$e_d = d - \hat{d}$$

- **PI Voltage Controller:**

$$\mu_{dc} = K_{pv}e_z + K_{iv} \int_0^t e_z dt$$

- **Experimental Results:** LDO-PI exhibited significantly improved voltage transient response and robustness to load and capacitor variations while maintaining low current THD (Tables 3.3 & 3.4) [[3]].

Chapter 4: State Estimation and Control via Improved SMO

- **Improved Sliding Mode Observer (SMO)** with an additional tuning parameter

$$K_o$$

to accelerate transient response without affecting steady-state THD.

- **Voltage Regulation Loop:**

$$C\dot{z} = \mu_{dc} + \hat{d} - d$$

$$\mu_{dc} = \lambda_c |e|^{1/2} \text{sign}(e) + \alpha_c \int_0^t \text{sign}(e) d\tau$$

- **SMO Observer:**

$$C\dot{\hat{z}} = K_o(u + f(\hat{e})), \quad f(\hat{e}) = \lambda_o |\hat{e}|^{1/2} \text{sign}(\hat{e}) + \alpha_o \int_0^t \text{sign}(\hat{e}) d\tau$$

- **Stability:** Proven via Lyapunov method, with bounded disturbance derivative and finite-time convergence.
- **Experiments:** SMO-SMC significantly outperformed conventional PI in voltage transient response and robustness to load and capacitance variations [[4]].

Chapter 5: PI Control of Three-Phase Neutral-Point-Clamped (NPC) Converters

- **NPC Converter** topology provides more voltage levels, reducing harmonic distortion and switching losses but introduces capacitor voltage imbalance challenges.
- **Control Modes:**
 1. **Voltage Oriented Control (VOC):** Three loops — voltage regulation, current tracking, and capacitor voltage balancing.
 2. **Direct Power Control (DPC):** Tracks power directly, eliminating current loop; utilizes hysteresis control.
- **Voltage Regulation Loop** with LESO compensating PI controller:

$$C\dot{z}_1 = \mu_{dc} - d$$

- **Power Tracking Loop:** Super-twisting SMC drives active/reactive power to references.
- **Capacitor Voltage Balancing:** Adaptive estimator and super-twisting SMC to suppress third harmonic disturbances.
- **Simulation Results:** LESO-based control significantly improved transient response and robustness against large load variations (Figs. 5.9–5.17) [[5]].

Chapter 6: Sliding Mode Control of Buck Converters

- **Buck Converter Model:**

$$L\frac{di_L}{dt} = -ri_L - v_{out} + uv_{in}$$

$$C\frac{dv_{out}}{dt} = i_L - \frac{v_{out}}{R_L}$$

- **Control Objectives:**
 - Inductor current tracking:
 - Output voltage regulation:

$$i_L \rightarrow i_L^*$$

$$v_{out} \rightarrow v_{ref}$$

- **Control Scheme:** Cascaded control with LESO-based super-twisting SMC for voltage loop, and super-twisting SMC for current loop.
- **Observer Design (LESO):**

$$C\dot{\hat{v}}_{out} = i_L^* - \hat{i}_{load} + \eta_1(v_{out} - \hat{v}_{out})$$

$$\dot{\hat{i}}_{load} = -\eta_2(v_{out} - \hat{v}_{out})$$

- **Simulation Results:** Proposed strategy showed better robustness to load, input voltage, and reference voltage variations than PI control [[6]].

Chapter 7: Model Predictive Control (MPC) of Three-Phase Two-Level Converters

- **System Model** in stationary (,) frame:

$$L\frac{di_{\alpha\beta}}{dt} = v_{\alpha\beta} - \frac{v_c}{2}u_{\alpha\beta} - ri_{\alpha\beta}$$

$$C\frac{dv_c}{dt} = \frac{1}{2}u_{\alpha\beta}^T i_{\alpha\beta} - \frac{v_c}{R_L}$$

- **Finite Set MPC:**
 - Predict switching states

$$u_{\alpha\beta}$$

from finite set (Table 7.1).

- Cost function:

$$g = \|p(k+1) - p^*\| + \|q(k+1)\|$$

- **Voltage regulation loop:** LESO-based PI control.
- **Power tracking loop:** Finite-set MPC for fast dynamic power control.
- **Simulation Results:** LESO-based MPC improved DC-link voltage transient response and robustness compared to conventional MPC [[7]].

Part II: Intelligent Control Methods

Chapter 8: Adaptive Control of Buck Converters

- **Two Adaptive Strategies:**
 1. **Single-Loop Adaptive Control:**
 - Directly regulates output voltage.
 - Back-stepping adaptive approach.
 2. **Double-Loop Adaptive Control:**
 - Outer voltage regulation loop.
 - Inner current tracking loop with sliding mode control.
 - **Lyapunov-based design** with adaptive laws for parameter estimation.
 - **Experiments:** Single-loop control offers faster transient, higher ripple; double-loop provides smoother output, less ripple but slower response [[8]].
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Chapter 9: Adaptive

$$H_\infty$$

Control of Three-Phase Two-Level Converters

- **Model:**

$$\dot{i}_{dq} = -\frac{r}{L}i_{dq} - \omega J i_{dq} + \frac{e_{dq}}{L} - \frac{1}{L}u_{dq}v_{dc}$$

$$\dot{v}_{dc} = -\frac{1}{R_L C}v_{dc} + \frac{1}{C}u_{dq}^T i_{dq}$$

- **Voltage Regulation Loop:** Adaptive controller regulating

$$v_{dc}$$

with unknown load and slow variation.

- **Current Tracking Loop:** Two

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controllers designed independently for d and q axis currents to track references.

- **Key Adaptive Controller:**

$$p^* = ke_1 + Cx_1\hat{\rho}$$

$$\dot{\hat{\rho}} = \eta x_1 e_1$$

- **Stability:** Proven via Lyapunov and Linear Matrix Inequality (LMI) techniques.
- **Simulation Results:** Adaptive

$$H_\infty$$

control outperformed ESO-SOSM and PI controllers in voltage drop and current THD (Table 9.3) [[9]].

Chapter 10: Adaptive Sliding Mode Control of Three-Phase Two-Level Converters

- **Problem:** Parameter uncertainties in

$$L, r, \omega$$

and unknown disturbance derivative bounds complicate classical SMC design.

- **Adaptive Super-Twisting Sliding Mode Control (ASMC):**
 - Adaptive gain laws to avoid a priori knowledge of disturbance derivative bounds.
- **Voltage Regulation Loop:** LESO combined with

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controller.

- **Current Tracking Loop:** Two ASMC controllers for d and q currents.
- **Key Formulation:**

$$\mu_j(s_j) = \lambda_j(t)|s_j|^{1/2}\text{sign}(s_j) + \alpha_j(t) \int_0^t \text{sign}(s_j)d\tau + k_{\lambda_j}(t)s_j + k_{\alpha_j}(t) \int_0^t s_j d\tau$$

- **Adaptive laws** update gains

$$\Gamma_d(t)$$

,

$$\Gamma_q(t)$$

based on sliding variables.

- **Simulation Results:** ASMC-

$$H_\infty$$

control showed faster voltage recovery and current tracking than PI control under load variation and parameter uncertainty [[10]].

Chapter 11: Adaptive Neural Network Control of Three-Phase NPC Converters

- **Radial Basis Function Neural Network (RBFNN)** approximates unknown nonlinearities:

$$\sup_{x \in \Omega} \|d(x) - \theta^T \xi(x)\| \leq \epsilon_m$$

where

$$\theta$$

is weight vector,

$$\xi(x)$$

is Gaussian basis function vector.

- **Control Structure:** DPC mode with three loops:
 1. **Voltage Regulation Loop:** Adaptive controller regulates sum of capacitor voltages.
 2. **Power Tracking Loop:** Two adaptive sliding mode controllers designed using RBFNN to track active/reactive power (Eqs. (11.24)-(11.33)).
 3. **Voltage Balancing Loop:**

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controller based on reduced-order observer to eliminate capacitor voltage imbalance.

- **Reduced-Order Observer** designed for harmonic disturbance estimation.
 - **Experiments:** Proposed RBFNN-based control outperformed PI control with faster transient response, smaller voltage drop, and better voltage balancing (Figs. 11.7–11.11) [[11]].
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12. Conclusion and Further Work

12.1 Conclusions

- Advanced disturbance observer-based sliding mode and PI controls significantly improve power converter robustness and transient performance.
- LESO and SMO observers enhance disturbance rejection in both two-level and NPC converters.
- Adaptive control strategies, including

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and ASMC, enable robustness against load variations and parameter uncertainties without requiring a priori disturbance bounds.

- Neural network-based adaptive controllers effectively handle nonlinearities and uncertainties in NPC converters.
- MPC combined with LESO offers fast power tracking with disturbance estimation.

12.2 Further Work

- Development of systematic parameter tuning methods beyond conservative Lyapunov-based designs.
- Extension to more converter topologies (e.g., flying capacitor, cascaded H-bridge).
- Consideration of networked multi-converter systems addressing communication issues and cyber-physical security.

Key Formulas Summary

Concept	Formula
PI Controller (d,q frame)	$G_{PI}^{dq}(s) = k_p + \frac{k_i}{s}$
PR Controller (, frame)	$G_{PR}^{\alpha\beta}(s) = k_p + \frac{k_i s}{s^2 + \omega^2}$
Super-twisting SMC	$u = u_1 + u_2, \quad \dot{u}_1 = -\lambda s ^{1/2}\text{sign}(s), \quad \dot{u}_2 = -\alpha\text{sign}(s)$
Voltage Regulation Loop Dynamics	$C\dot{z}_1 = \mu_{dc} - d, \text{ where } z_1 = \frac{V_{dc}^2}{2}$

Concept	Formula
LESO Observer	$\begin{cases} C\dot{\hat{z}}_1 = u - \hat{z}_2 + \beta_1(z_1 - \hat{z}_1) \\ \dot{\hat{z}}_2 = -\beta_2(z_1 - \hat{z}_1) \end{cases}$
Adaptive Control Law	$\dot{\hat{\theta}} = -\eta x_1 e_1$
Model Predictive Control Cost	$g = \ p(k+1) - p^*\ + \ q(k+1)\ $
RBF Neural Network Approximation	$d(x) \approx \theta^T \xi(x)$
Adaptive Sliding Mode Control	$\mu_j(s_j) = \lambda_j(t) s_j ^{1/2}\text{sign}(s_j) + \alpha_j(t) \int_0^t \text{sign}(s_j)dt + \dots$

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and

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This detailed summary captures the essence of advanced control methodologies for power converters, combining theoretical modeling, observer-based disturbance rejection, nonlinear and adaptive control methods, and practical validation through simulations and experiments.
