Energy Conversion
Circuit Laboratory

Fixed-time Sliding Mode Control for Three-phase PWM Rectifiers

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ABSTRACT

This paper proposes a robust Sliding Mode Control (SMC) strategy for a three-phase six-switch PWM rectifier. The system dynamics are formulated in the synchronous dq reference frame, enabling accurate modeling and effective control design. A fixed-time reaching law is employed to drive the system states to the sliding surface, improving convergence speed and enhancing robustness against parameter uncertainties and load disturbances. Lyapunov-based analysis guarantees closed-loop stability. The converter with the proposed controller is well suited for battery charging station systems, as well as grid-connected and renewable energy power transmission applications. Simulation results confirm stable DC voltage regulation and robust performance under varying operating conditions.

1. Introduction

Three-phase pulse-width modulation (PWM) rectifiers are widely used in electric vehicle charging systems, renewable energy conversion, motor drives, and grid-connected applications due to their high-power factor, bidirectional power flow capability, and low harmonic distortion [1], [2]. However, the DC-link voltage of PWM rectifiers is easily influenced by parameter uncertainties, load variations, and external disturbances, which may degrade system stability and power quality [1]. Therefore, robust control strategies for PWM rectifiers have attracted significant research interest.

Conventional control methods such as proportional–integral (PI) control, hysteresis control, and predictive control have been extensively studied [1], [2]. Nevertheless, their performances may deteriorate under uncertain operating conditions. In contrast, Sliding Mode Control (SMC) provides strong robustness against disturbances and parameter variations due to its nonlinear switching characteristics [1], [3]. Recently, fixed-time control theory has been introduced to improve the convergence performance of conventional SMC by guaranteeing convergence within a bounded time independent of initial conditions [3].

Motivated by these advantages, this paper proposes a robust Sliding Mode Control strategy with a fixed-time reaching law for a three-phase six-switch PWM rectifier. The proposed controller is designed in the synchronous dq reference frame and analyzed using Lyapunov stability theory. Simulation results demonstrate stable DC voltage regulation and robust dynamic performance under varying operating conditions.

2. Proposed Control Method

2.1 Mathematical Model

Fig.1 shows the block diagram of the proposed method for

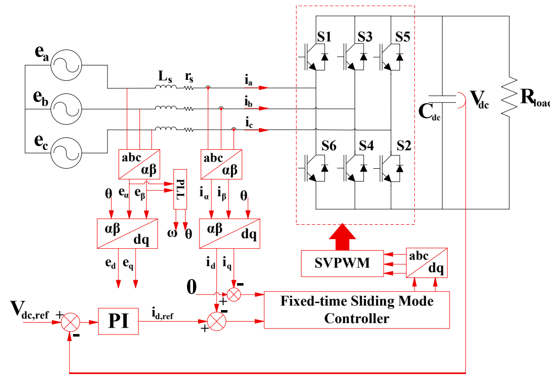

Fig.1 Block diagram of the proposed control strategy for a three-phase PWM rectifier.

the three-phase PWM rectifier, where e_a, e_b, e_c are the grid-side three-phase AC voltages, i_a, i_b, i_c are the grid-side three-phase AC currents, L is the grid-side filter inductance, r is the grid-side equivalent resistance, C is the DC-link capacitance, V_{dc} is the output DC voltage, and R_L is the load resistance.

According to [1], the mathematical model of the rectifier in *dq* coordinate can be expressed as follows

$$L\frac{di_d}{dt} = e_d - ri_d - u_q + \omega L i_q, \quad (1)$$

$$L\frac{di_q}{dt} = e_q - ri_q - u_d - \omega L i_d, \quad (2)$$

where ω is the angular frequency of the grid voltage, u_d and u_q are the control inputs of the rectifier in the d-axis and q-axis, respectively, e_d and e_q are the components of the grid-side AC voltage in dq coordinate, and i_d and i_q are the components of the grid-side AC current in dq coordinate.

2.2 Fixed-time Sliding Mode Controller

Consider the mathematical model above as a nonlinear system which can be described

$$\dot{x} = f(x) + g(x)u, \quad (3)$$

where x is the state variable, $f(x)$ presents the internal dynamics of the system, $g(x)$ is the control effectiveness, u is the control signal. With the tracking error $e = x - x_{ref}$, the sliding surface is defined as

$$s = e. \quad (4)$$

Hence, the derivative of sliding surface is expressed by

$$\dot{s} = \dot{e} = f(x) + g(x)u + \Delta. \quad (5)$$

The control signal u is divided into equivalent control and switching control $u = u_{eq} + u_{sw}$, where the equivalent control can be computed by

$$u_{eq} = -\frac{f(x)}{g(x)}. \quad (6)$$

Reusing the reaching law of SMC in [3], forcing the actual sliding dynamics to follow below

$$\dot{s} = -k_1|s|^{\alpha} sign(s) - k_2|s|^{\beta} sign(s), \quad (7)$$

where $k_1 > 0, k_2 > 0$ are reaching gains, $0 < \alpha < 1 < \beta$ are nonlinear power exponents determining the convergence characteristics of the sliding dynamics. From (5) and (7), the switching control can be found by

$$u_{sw} = \frac{-k_1|s|^{\alpha} sign(s) - k_2|s|^{\beta} sign(s)}{g(x)}. \quad (8)$$

To analyze the stability of the controller, considering the one-dimensional Lyapunov function $V(s) = \frac{1}{2}s^2$. It is found that

$$\dot{V}(s) = s\dot{s} = -k_1|s|^{\alpha+1} - k_2|s|^{\beta+1} < 0. \quad (9)$$

By using this reaching law, the system becomes stable after a fixed time $T \le T_{max} = \frac{1}{k_1(1-\alpha)} + \frac{1}{k_2(\beta-1)}$.

2.3 Fixed-time SMC for Three-phase PWM Rectifier

From (1), (2), and (3), the dynamic functions of the system can be obtained such that

$$f_d(x) = \frac{1}{L}e_d - \frac{r}{L}i_d + \omega i_q, \quad (10)$$

$$f_q(x) = \frac{1}{L}e_q - \frac{r}{L}i_q - \omega i_d, \quad (11)$$

$$g_d(x) = g_q(x) = -\frac{1}{L}, \quad (12)$$

Hence, the control signal can be calculated and applied to the control blocks.

3. Simulation Results

Simulation is carried out to verify the effectiveness of the proposed method under both balanced and unbalanced grid conditions. In this article, only one unbalanced case, as shown in Fig. 2, is considered.

The performance of the proposed controller was compared with that of a conventional PI controller designed with a crossover frequency of 1592 Hz and a phase margin of 63°. Since both methods employ the same outer voltage loop using a PI controller (crossover frequency of 265 Hz, and phase margin of 68°), the comparison mainly focuses on the current-tracking performance of the inner loop. The parameters of the proposed controller are selected as $k_1 = 1900$, $k_2 = 100, \alpha = 0.5$, $\beta = 5$ based on the fixed-time stability bound derived from Lyapunov analysis, resulting in a maximum settling time of $3.55\,ms$. Here, $\alpha = 0.5$ is chosen to balance convergence speed and robustness, while $\beta = 5$ is selected to accelerate convergence near the sliding surface and reduce chattering.

Fig. 3 shows the steady-state current in the dq frame, while Fig. 4 presents the transient current response when the load power changes from 10 kW to 20 kW at $t = 0.2s$. It can be observed that the proposed method reduces current ripple by approximately 20% (in balanced condition) and 22% (in unbalanced condition), and achieves a smoother transient response.

As a result, the voltage regulation performance is also improved due to the enhancement of the inner loop, as shown in Fig. 5 and Fig. 6.

4. Conclusion

This paper proposes a fixed-time Sliding Mode Control strategy for a three-phase PWM rectifier in the synchronous dq reference frame. The proposed controller achieved robust current tracking and stable DC-link voltage regulation under both balanced and unbalanced grid conditions, as well as load power variations. Simulation results demonstrate reduced current ripple, improved transient response, and smaller DC-link voltage fluctuations compared with the conventional PI controller.

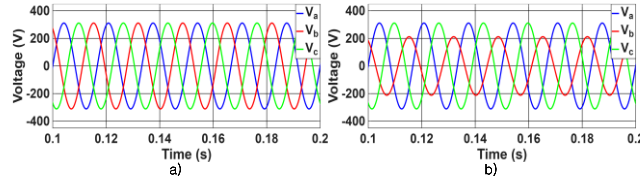

Fig.2 Three-phase grid voltage under (a) balanced, and (b) unbalanced voltage conditions.

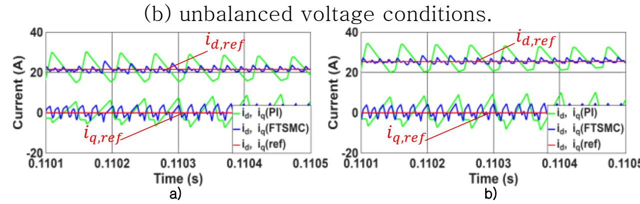

Fig.3 Steady - state dq current under (a) balanced, and (b) unbalanced grid conditions.

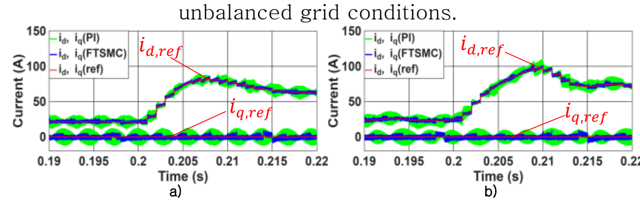

Fig.4 Transient response of the dq current when load power changes under (a) balanced, and (b) unbalanced grid conditions.

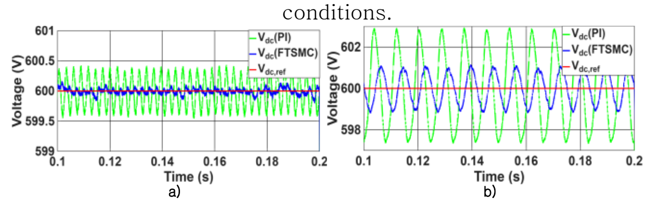

Fig.5 DC-link voltage under (a) balanced, and (b) unbalanced grid conditions.

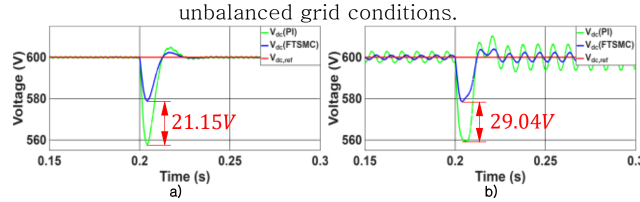

Fig.6 Transient response of the DC-link voltage under (a) balanced, and (b) unbalanced grid conditions.

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1. Introduction

❖ **Motivation**

- Problem: The DC-link voltage of three-phase PWM rectifiers is highly sensitive to disturbances like sudden load power changes.
- Limit: Conventional controllers (PI, hysteresis, predictive) degrade under varying operating conditions and recover too slowly.
- Solution: SMC ensures strong robustness, but fixed-time control is critical to guarantee bounded-time convergence.

❖ **Why fixed-time convergence is necessary?**

- Fixed-time control guarantees that the system error converges to zero within a maximum settling time T_{max}, completely independent of initial states or error magnitudes.
- In high-power applications, letting a voltage deviation last too long can trigger catastrophic component failures (e.g., IGBT burnout or capacitor degradation).
- forces the DC-link voltage to stabilize within a strict, predefined time window $T \leq T_{max}$, ensuring maximum grid reliability and system safety even under worst-case disturbances.

❖ **Proposed:**

- A fixed-time reaching law-based SMC is proposed for a three-phase PWM rectifier, with its stability verified by Lyapunov analysis.

2. Proposed Method

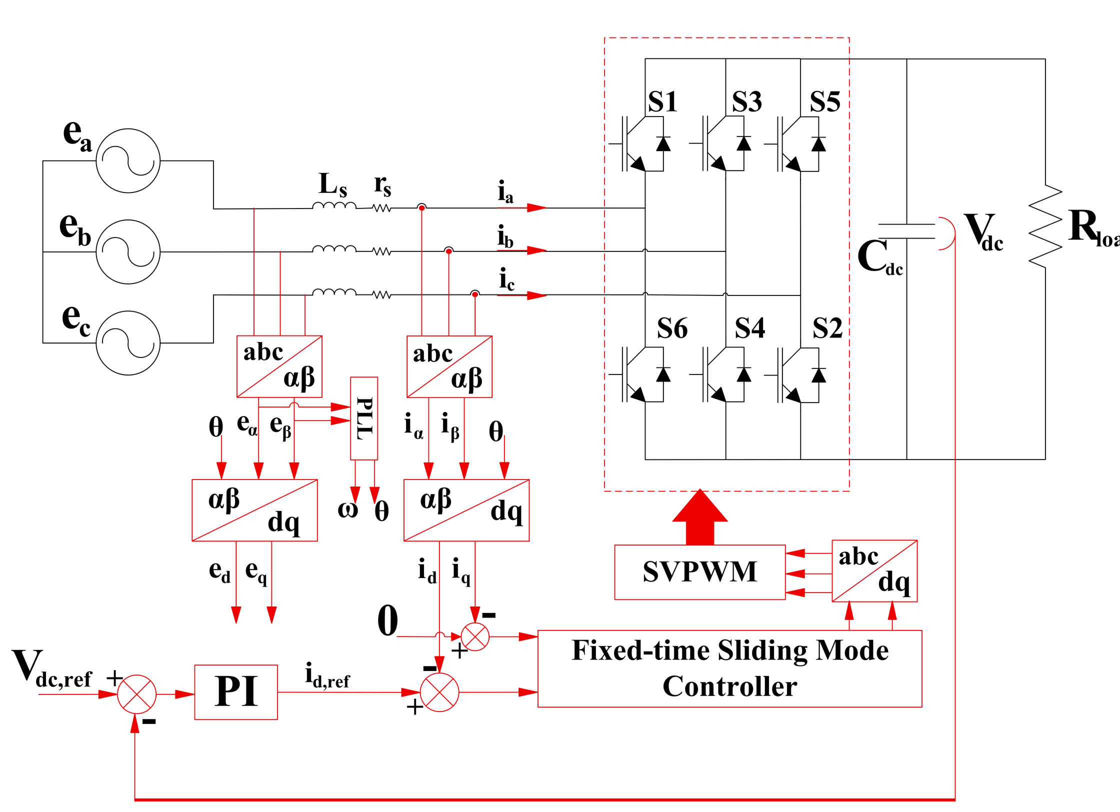
❖ **Fixed-time Sliding Mode Controller**

- Standard model of nonlinear systems: $\dot{x} = f(x) + g(x)u$.
- Sliding surface: $s = e = x - x_{ref}$.
- Equivalent control: $u_{eq} = -g^{-1}(x)f(x)$.
- Switching control: $u_{sw} = \frac{-k_1|s|^{\alpha}sign(s) - k_2|s|^{\beta}sign(s)}{g(x)}$,

where $k_1 > 0, k_2 > 0$ are reaching gains, $0 < \alpha < 1 < \beta$ are nonlinear power exponents determining the convergence characteristics of the sliding dynamics.

- Control signal: $u = u_{eq} + u_{sw}$.
- Lyapunov function $V(s) = \frac{1}{2}s^2 \Rightarrow \dot{V}(s) = s\dot{s} = -k_1|s|^{\alpha+1} - k_2|s|^{\beta+1} < 0$.
- The system converges within a fixed time: $T \leq T_{max} = \frac{1}{k_1(1-\alpha)} + \frac{1}{k_2(\beta-1)}$.

❖ **Mathematical Model**



Block diagram of the proposed control strategy for a three-phase PWM rectifier

- The mathematical model of the rectifier in d-q coordinate:

$$L\frac{di_d}{dt} = e_d - ri_d - u_q + \omega L i_q,$$
$$L\frac{di_q}{dt} = e_q - ri_q - u_d - \omega L i_d.$$

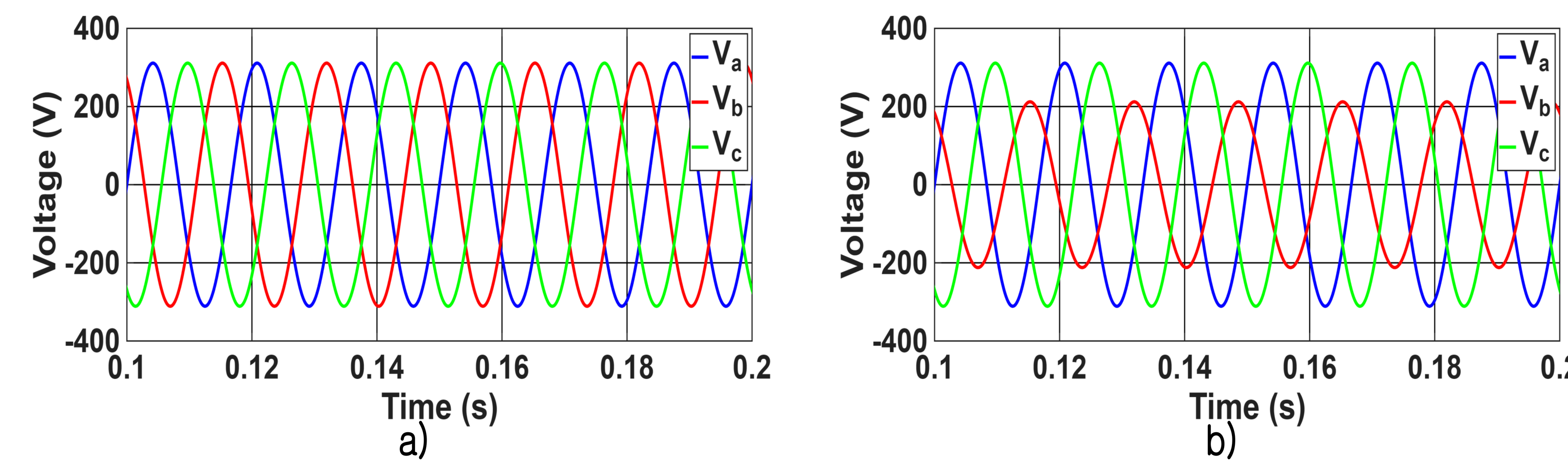
- The dynamic functions of the system can be obtained such that:

$$f_d(x) = \frac{1}{L}e_d - \frac{r}{L}i_d + \omega i_q,$$
$$f_q(x) = \frac{1}{L}e_q - \frac{r}{L}i_q - \omega i_d,$$
$$g_d(x) = g_q(x) = -\frac{1}{L}.$$

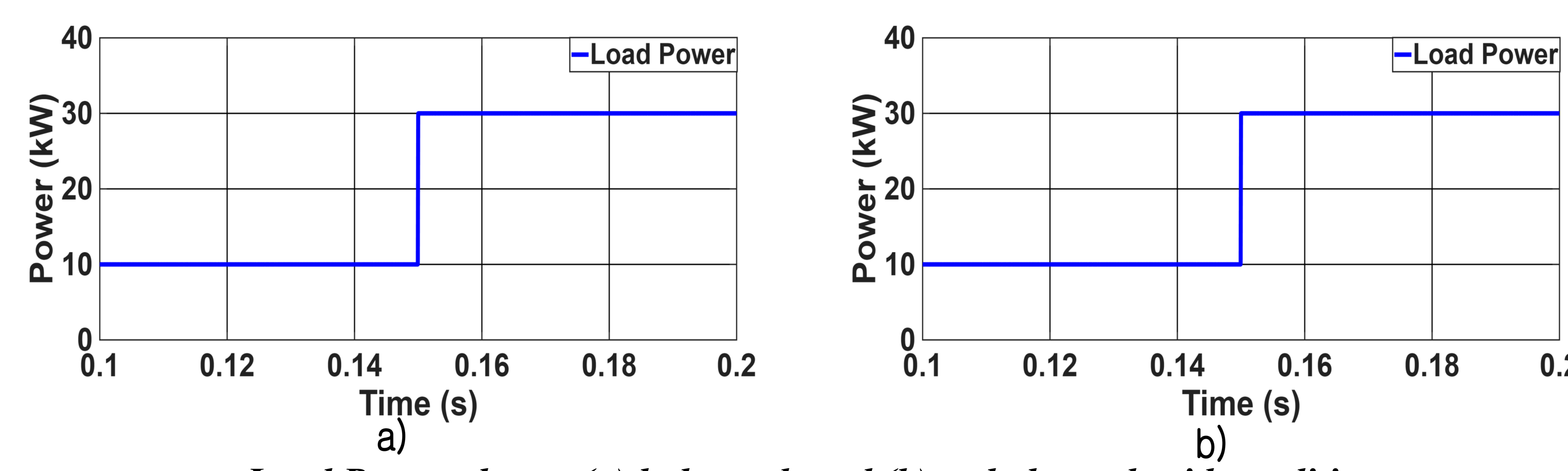
3. Simulation Results

Simulation Parameters

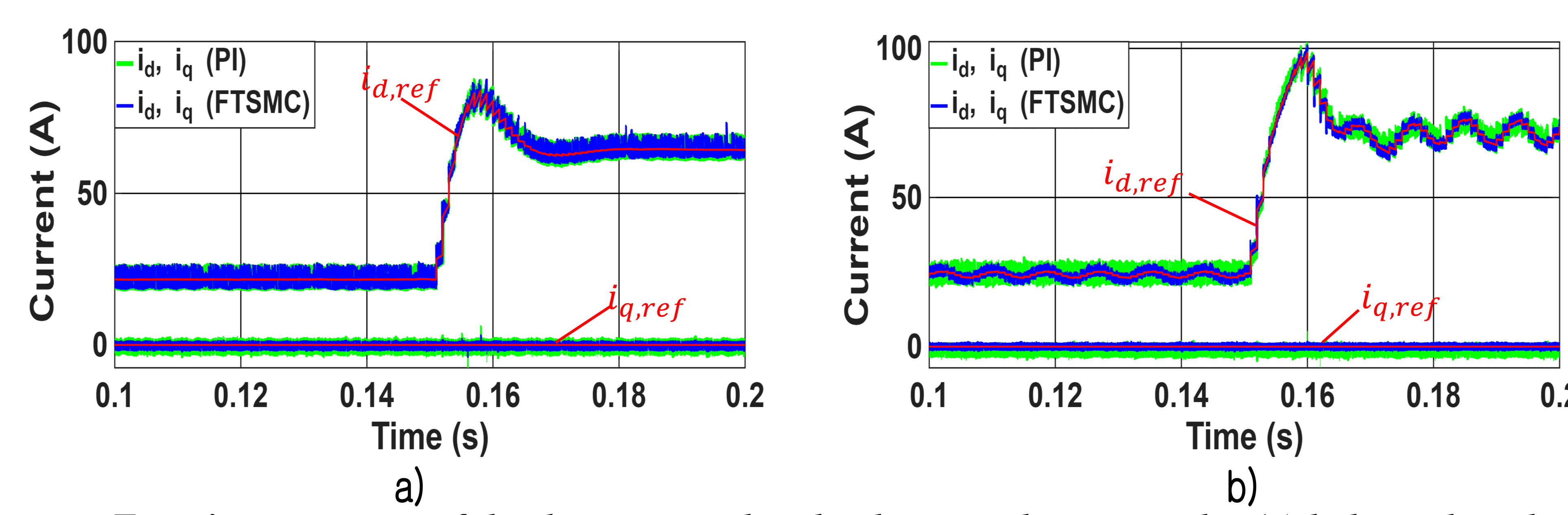
Outer Voltage PI Controller (Both methods)		Crossover frequency: 265 Hz; Phase margin: 68°	
Inner current controller	Conventional PI	Crossover frequency: 1592 Hz; Phase margin: 63°	
	Proposed FTSMC	$k_1 = 1900; k_2 = 100; \alpha = 0.5; \beta = 5; T_{max} = 3.55ms$	
Grid conditions		Balanced Voltage conditions	Unbalanced Voltage conditions



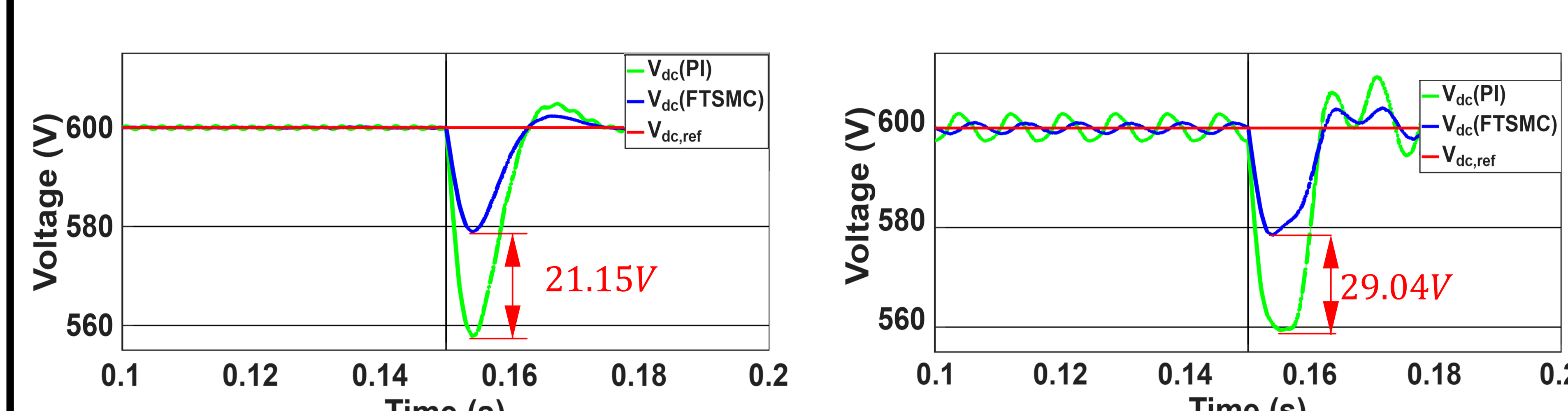
Three-phase grid voltage under (a) balanced and (b) unbalanced voltage conditions



Load Power change(a) balanced, and (b) unbalanced grid conditions.



Transient response of the dq current when load power changes under (a) balanced, and (b) unbalanced grid



Transient response of the DC-link voltage under (a) balanced, and (b) unbalanced grid conditions.

❖ Performance improvements in the voltage regulation using FTSMC over PI:

- Balanced condition: ~20% reduction in overshoot voltage,
- Unbalanced condition: ~22% reduction in overshoot voltage.

4. Conclusion

- A Fixed-Time Sliding Mode Control a three-phase PWM rectifier in the synchronous *dq* reference frame.
- Achieved robust current tracking and stable DC-link voltage regulation under balanced/unbalanced grid conditions and load power variations.
- Demonstrated reduced current ripple, faster transient response, and smaller DC-link voltage fluctuations compared with a conventional PI controller.