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Hybrid PID-LQR Controller for Dynamic Response and Stability Enhancement of Synchronous Generator's AVR System

Paulinus C. Eze[1*], Stanley U. Nwadike[2],
Dennis C. Oyiogu[3], Mercy Chinenye Iroegbu[4]
[1,4]Imo State University, Owerri, Nigeria; [2]Federal Polytechnic Nekede, Owerri, Nigeria;
[3]Nnamdi Azikiwe University, Awka, Nigeria
paulinuseze1@gmail.com

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Abstract

The delay in the transition from transient to steady-state conditions in exciter field dynamics is identified as a key factor contributing to inefficiencies in maintaining a stable terminal output voltage in synchronous generators. This delay often results in significant overshoot in the generator's output voltage, negatively affecting the performance of connected loads such as electric motors. This study aims to develop and evaluate a control strategy based on Proportional-Integral-Derivative and Linear Quadratic Regulator (PID-LQR) models to mitigate this issue. A hybrid control system was designed to enhance voltage stability within the Automatic Voltage Regulator (AVR) of an exciter-based synchronous generator. Using MATLAB simulations, the proposed PID+I-LQR controller demonstrated a reduction in system overshoot from 60.9547% to 1.1524%, representing a 98.1% improvement in voltage stability. Comparative analysis with other control models confirmed the superior performance of the PID-LQR-based controllers in achieving smooth voltage response and convergence to a stable terminal voltage, with the exception of

LQI and PID+PD-LQR controllers. The findings underscore the effectiveness of PID-LQR controllers in improving dynamic response and voltage regulation in synchronous generator systems.

Keywords: AVR; Control system; Exciter; PID-LQR controllers; Synchronous generator

INTRODUCTION

In a large interconnected power system, manual regulation is much complicated and therefore automatic generation and voltage regulation is necessary. Usually, generated voltage fluctuates mainly due to either the variation in the load, speed, temperature or power factor. A variation in the terminal voltage can have adverse effect on connected equipment. In fact, any deviation from these physical parameters can result in decrease in performance and lifetime of these synchronous machines. In order to maintain a constant voltage level, Automatic Voltage Regulators (AVRs) are used at each generating station/synchronous generators. Also, the need for AVR becomes very necessary because the voltage supply of generators should be maintained at steady or constant value otherwise the performance of motors, lights etc. will be affected. However, using only AVR without a controller will not yield desired result and as such, it is necessary to integrate a controller as a part of the AVR closed loop control system. A good excitation control, indeed, has proven to be very efficient to support the voltage on the power system, to enhance its transient stability and to damp its oscillations. Doing this ensures that desired voltage level and stability is achieved at lesser time even in the presence of parameter variation.

AVRs may be employed for regulating Alternating Current (AC) or Direct Current (DC) voltage (Okoye et al., 2021; Verna & Mishra, 2014). An AVR system is usually designed with a controller to enhance its operation by ensuring that the output voltage at the terminal is kept as close as possible to desired level of voltage to achieve minimal or zero deviation. The operation of AVR is such that when the generator's terminal voltage is disturbed because of the application of certain load the excitation field changes which can alter the voltage level at the terminal. Therefore, the controller is forced to act according to this deviation by producing a correctional action that coordinate the generator's exciter system.

Excitation control of generators is a very important topic in the field of power systems. There are various control strategies that have been proposed and implemental for AVR system in theory and in practice. Among these control strategies, the proportional integral and derivative (PID) controller is the most common control algorithm used in industry (Eze et al., 2020; Shern et al., 2019). The popularity of the PID control algorithm lends credence to the fact that it is simple and easy to implement. In recent times, classical PID is commonly modified by either optimizing its parameters with intelligent based algorithm such as in Eze et al. (2024) or integrating its algorithm with another control model for instance in Ekengwu et al. (2024) and Eze et al. (2024). These approaches are being used recently in enhancing the stability of PID controlled AVR systems.

An optimal transient response and stability was achieved using Jaya Optimization Algorithm (JOA) based Fractional Order PID (FOPID) in AVR system (Jumani et al., 2020). Among AVR system designs, Gradient-Based Optimization (GBO) tuned FOPID was observed to offer the finest optimal transient response and improved stability (Alybawi et al., 2024). Hybrid Simulated Annealing-Manta Ray Foraging Optimization (SA-MRFO) was used to optimize ideal PID, real PID, fractional order PID (FOPID), and PID plus second-order Derivative (PIDD^2) and the dynamic response analysed revealed that SA-MRFO-PIDD^2 yielded the most enhanced performance in terms of rise time, settling time, and overshoot (Micev et al., 2020). Cuckoo Search (CS) optimized PID provided the most effective performance for dynamic response characteristics of AVR system compared to other control methods (Govindan. 2020). The trade-off between dynamic response and the stability margin of AVR system was improved in addition to parameter variations and handling of perturbation using Symbiotic Organization Search (SOS) tuned PID controller (Çelik & Durgut, 2018). The performance of the dynamic response of AVR system in a hydro power plant (Myanmar) was improved using stabilizer and PID (Yu & Zaw, 2019).

The related previous works have been achieved basically using the transfer function model of the AVR system. Considering the associated limitation of such output-input relation model, there will be no sufficient knowledge about the dynamic of internal variables of the system such as the exciter behaviour. Hence, in this paper a hybrid optimal PID adjusted Linear Quadratic Regulator (PID-LQR) is used to enhance the dynamic response of AVR system for synchronous generator minimum or zero deviation.

METHODS

First, the mathematical model of the system was presented. This was followed by LQR and PID-LQR designed using MATLAB Syntax and PID tuner. The embedded blocks of the Simulink were used to model the system. Three subsections were used to clearly and concisely present the approach adopted for the designed. These subsections are: description of the system and its dynamic model, LQR control system design, and PID-LQR controller design.

System Description and Mathematical Model

A block diagram representation of the linearized system is shown in Figure 1. It consists of an amplifier, which acts as a conventional AVR to energies the exciter system. The exciter field voltage is then adjusted to provide a signal to regulate the output voltage of the synchronous generator. This results in setting the terminal voltage of the generator to expected profile. Once the expected voltage level is reached, the error signal drops to zero or to acceptable value very much near to zero and the generator settles. Otherwise, the deviation of the output voltage from the desired input voltage may cause instability if it persists and expected voltage profile will not be reached. The system is modelled as a synchronous machine connected to an infinite bus that uses exciter and AVR subunits to maintain a voltage profile at the output (Ibraheem, 2011). The parameters of the system are listed in Table 1.

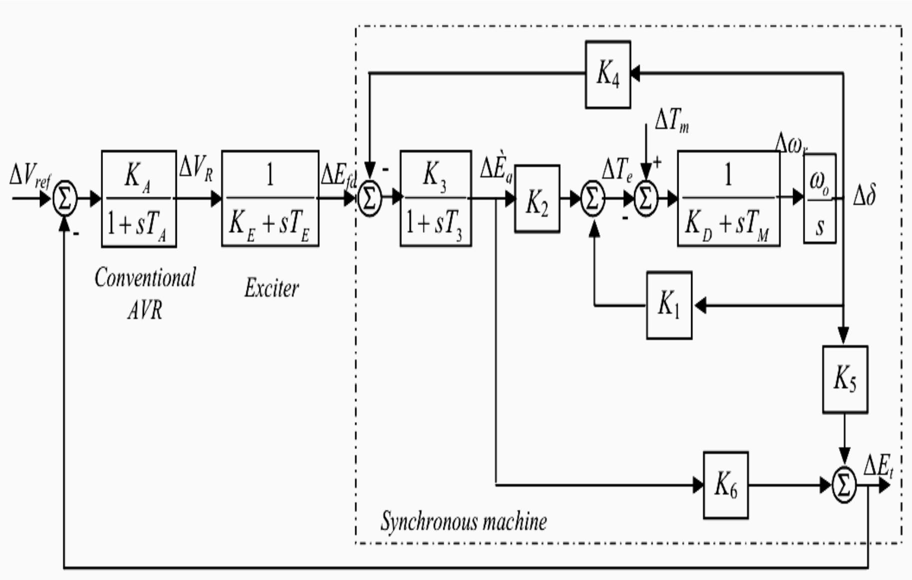

Figure 1 : AVR system with synchronous generator (Ibraheem, 2011)

Table 1. Excitation system parameters (Ibraheem, 2011)

Parameter	Definition	Value	Unit
K_D	Damping factor = torque (pu)/speed (pu)	2	pu
T_M	Mechanical starting time	8	s
K_A	Conventional AVR gain	50	-
T_A	Conventional AVR time constant	0.02	s
K_E	Exciter gain	0.17	-
T_E	Exciter time constant	0.95	s
K_1	Synchronous machine factor	1.0753	-
K_2	Synchronous machine factor	1.2581	-
K_3	Synchronous machine factor	0.3071	-
K_4	Synchronous machine factor	1.7124	-
K_5	Synchronous machine factor	-0.0476	-
K_6	Synchronous machine factor	0.4972	-
T_f	Field circuit time constant	1.8	s
ω_o	System frequency	50	Hz

The reduced block diagram of the exciter based AVR control is shown in Figure 2. The figure has the designed controller connected with the amplifier (conventional AVR) to form the hybrid controlled AVR system.

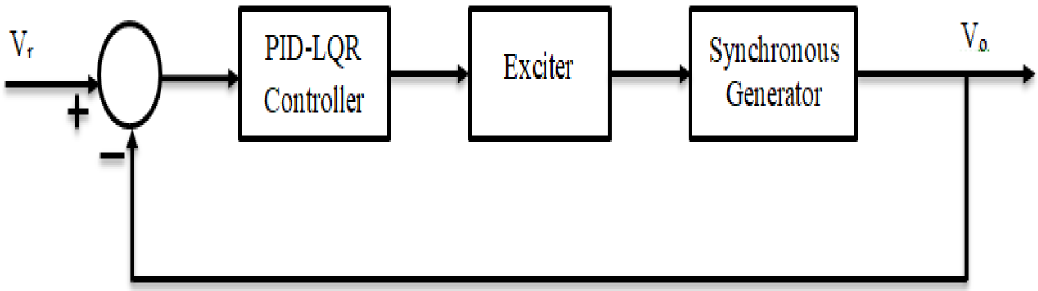

Figure 2 : AVR control system with PID-LQR controller

The state-space equations of the exciter and synchronous generator used in describing the dynamic equation of the system is a Single Input Multiple Output (SIMO) define in Equations (1) and (2) (Ibraheem, 2011). With values of the parameters in Table 1 substituted, the state matrix (A), the input matrix (B), and the output matrix (C) were established.

$$\dot{x} = \begin{bmatrix} -\frac{K_E}{T_E} & 0 & 0 & 0 \\ \frac{K_3}{T_3} & -\frac{1}{T_3} & 0 & -\frac{K_3K_4}{T_3} \\ 0 & -\frac{K_2}{T_M} & -\frac{K_D}{T_M} & -\frac{K_1}{T_M} \\ 0 & 0 & \omega_o & 0 \end{bmatrix} x(t) + \begin{bmatrix} \frac{1}{T_E} \\ 0 \\ 0 \\ 0 \end{bmatrix} u(t) \tag{1}$$

$$y = \begin{bmatrix} 0 & K_6 & 0 & K_6 \\ 0 & 0 & 1 & 0 \end{bmatrix} x(t) + D = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tag{2}$$

$$A = \begin{bmatrix} -0.179 & 0 & 0 & 0 \\ 0.171 & -0.556 & 0 & -0.292 \\ 0 & -0.157 & -0.25 & -0.134 \\ 0 & 0 & 50 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 5.882 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \quad C = \begin{bmatrix} 0 & 0.4972 & 0 & -0.0476 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

Design of Linear Quadratic Regulator

The first step in the design of LQR is to determine the state-space model of the system. Having established the system state-space model, LQR system is designed to minimize a quadratic cost function defined by:

$$J = \frac{1}{2}\int_{t=0}^{t=t_f} (x^T(t)Qx(t) + u^T(t)Ru(t))dt \tag{3}$$

In Equation (3), Q and R are the state and control law weighting matrices. The values of these matrices are determined by continuous iteration and by this equation, the optimal control provided by the LQR is guaranteed. Equations (4) and (5) define the optimal control law, u and the optimal gain matrix, K.

$$u = Kx \tag{4}$$

$$K = -R^{-1}B^TP \tag{5}$$

where P is the matrix of the Algebraic Riccati Equation (ARE). The determined Q matrix and at fixed R and the corresponding P matrix and K matrix are:

$$Q = \begin{bmatrix} 0.1 & 0 & 0 & 0 \\ 0 & 0.1 & 0 & 0 \\ 0 & 0 & 0.1 & 0 \\ 0 & 0 & 0 & 0.1 \end{bmatrix}, R = [1], P = \begin{bmatrix} -0.3011 + 2.5765\mathrm{i} \\ -0.3011 - 2.5785\mathrm{i} \\ -0.3392 + 0.0000\mathrm{i} \\ -1.8558 + 0.0000\mathrm{i} \end{bmatrix}, K = \begin{bmatrix} 0.3081 \\ 0.2351 \\ -0.2505 \\ 0.0255 \end{bmatrix}^T$$

Therefore, the control law for the designed LQR in Equation (4) is given by:

$$u = [0.3081 \quad 0.2351 \quad -0.2505 \quad 0.0255]x \tag{6}$$

Design of PID Optimized LQR

The classical model of the PID is mathematically expressed in Equation (7) for a control interval of initial time, t_o and final time, t_f:

$$u_{PID} = K_p e(t) + K_i \int_{t_o}^{t_f} e(t)dt + K_d \frac{de(t)}{dt} \tag{7}$$

where K_p is the proportional gain, K_i is the integral gain, and K_d is the derivative gain. The expression $e(t)$ is the error, and it is defined as $e(t) = V_r - V_o$, as shown in Figure 2. Thus, Equation (7) can be redefined by:

$$u_{PID} = K_p(V_r - V_o) + K_i \int_{t=0}^{t_f} (V_r - V_o)dt + K_d \frac{d(V_r - V_o)}{dt} \tag{8}$$

The derivative of V_r is zero because it is constant. Therefore, Equation (8) can be represented for the output of the PID controller as:

$$u_{PID} = K_p(V_r - V_o) - K_d \frac{dV_o}{dt} K_i \int_{t=0}^{t_f} (V_r - V_o)dt \tag{9}$$

In the system, the PID uses its control variable u_{PID} to optimize the control law u of the LQR. This results in a new control action for exciter field winding that influences the terminal voltage of the synchronous accordingly and in order to maintain it at a steady-state and desired value. This is given by:

$$u_{PID-LQR} = u_{PID}(Kx) = \left[K_p K(V_r - V_o) - K_d K \frac{dV_o}{dt} K_i K \int_{t=0}^{t_f} (V_r - V_o)dt\right] x \tag{10}$$

Or $u_{PID-LQR} = \left[K_{pk} e(t) - K_{dk}\dot{e} + K_{ik} \int_{t=0}^{t_f} e(t)dt\right] x$ (11)

where $K_{pk} = K_p K$, $K_{dk} = K_d K$, and $K_{ik} = K_d K$. These parameters are optimized by adjusting the gains of PID controller overtime. The values of K_p, K_i, and K_d are 1.024, 0.001, and 0.010932, respectively.

With the PID-LQR controller designed, other versions of it were formulated such as Linear Quadratic Integrator (LQI), PID+D-LQR, PID+PD-LQR, and PID+I-LQR. The same PID gains were used in all cases except for LQI where the integral gain was 0.005.

RESULTS AND DISCUSSION

The results of the computer simulation tests conducted in MATLAB/Simulink are presented in this section under three scenarios: responses of conventional AVR control system (without controller), LQR and PID-LQR control AVR system, and comparison with other controllers such as PID plus Pre-filter (PID+F) implemented in Okoye et al. (2021), and Ezenugu and Nwokonko (2024) and Proportional Integral and Double Derivative (PIDD) in Okafor et al. (2024) to a certain the performance effectiveness of the designed hybrid algorithm for the AVR system.

Figures 3 and 4 show the responses of the system in terms of exciter filed and generator output terminal voltage for unit step in signal when controlled conventionally (i.e. without controller), with LQR, and the PID-LQR based algorithms. The numerical values for each response curve are presented in Table 2.

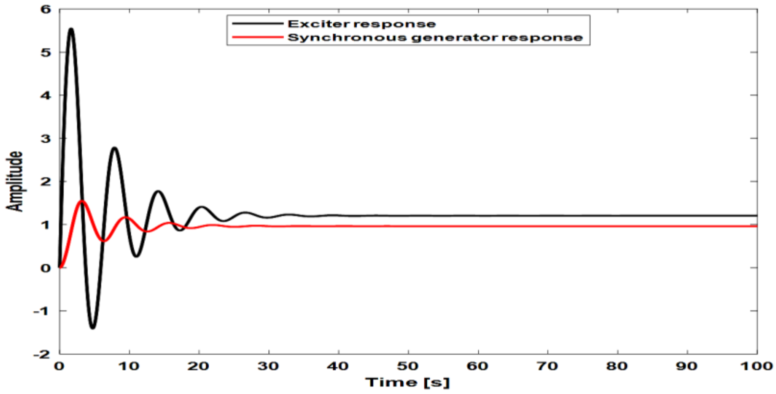

Figure 3 : Exciter and generator responses for conventional AVR

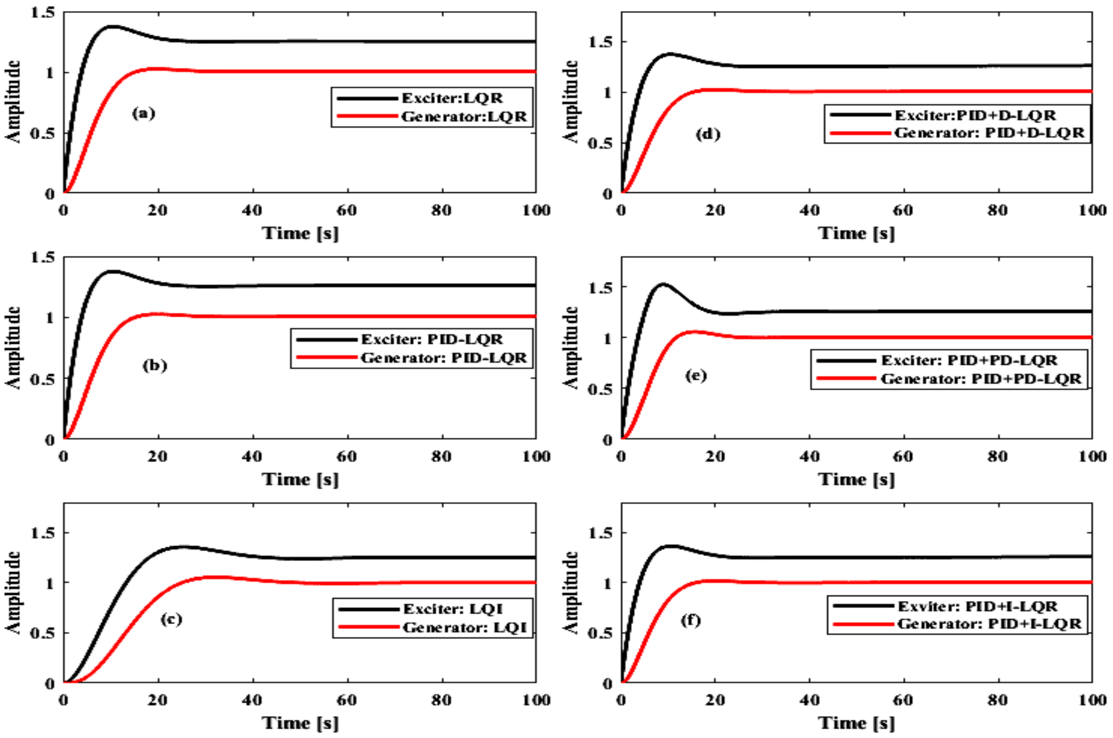

Figure 4 : Exciter and generator responses for: (a) LQR, (b) PID-LQR, (c) LQI, (d) PID+D-LQR, (e) PID+PD-LQR, (f) PID+I-LQR controlled AVR systems

Table 2. Numerical evaluation of conventional, LQR, and PID-LQR AVR systems

Controller	Peak value	% Overshoot	Rise time (s)	Transient time (s)	Settling time (s)	Steady-state error
			Exciter field response			
Conventional AVR	5.5454	360.239	0.1680	24.2981	33.3150	0.2049
LQR	1.3754	9.6424	4.5180	19.8784	19.8784	0.1298
PID-LQR	1.3762	9.0355	4.5766	19.1337	19.1337	0.1369
LQI	1.3569	8.4944	12.1115	37.7278	37.7278	0.2507
PID+D-LQR	1.3750	8.9443	4.5862	19.1248	19.1248	0.2621
PID+PD-LQR	1.5231	21.2413	3.9905	17.2420	17.2420	0.2563
PID+I-LQR	1.3654	8.3966	4.6393	18.4502	18.4502	0.2597
			Generator output terminal response			
Conventional AVR	1.5505	60.9547	1.2163	22.7394	22.7394	0.04
LQR	1.0245	2.1499	9.3820	21.3379	21.3379	0.00
PID-LQR	1.0255	1.6555	9.4982	14.4280	14.4280	0.01
LQI	1.0547	5.4693	15.1188	42.4085	42.4085	0.00
PID+D-LQR	1.0252	1.6197	9.5179	14.4685	14.4685	0.01
PID+PD-LQR	1.0585	5.3928	7.7181	21.0579	21.0579	0.04
PID+I-LQR	1.0182	1.1524	9.6233	14.7456	14.7456	0.01

It can be deduced from Table 2 that the output (or response) of the synchronous generator depends on the transient dynamics of the exciter. As shown in the table, without any controller implemented as part of the system, the exciter field response revealed very high oscillation to unit input electrical signal at the early stage of its response to unit input signal for 30 s. Even though the conventional AVR system achieved generator output (or final value) of 1.0367 which is near or almost the same as the desired unit input electrical signal, it has high oscillation at the early state of its response considering the magnitude of the overshoot (i.e. 60.9547%). This may be due to the variation (or delay) between the transient time 24.2981 s and the settling time 33.3150 s of the exciter system. This gap or delay of 9 s required by the exciter dynamic to move from transient state to steady (or convergence) state in the conventional mode can be attributed to the oscillation or cycling associated with the response of the generator at the early stage as shown in Figure 3. Hence, there is need for a controller that will address this problem.

With the integration of LQR and PID-LQR based models separately at a time in the system, the responses in Figures 4a-f were obtained. It can be seen from Table 2 that the delay or gap in system response in the conventional state was addressed as the transient time and settling time of the exciter circuit were made the same in all cases. Thus, there is no more any delay recorded when the exciter dynamic moved from transient state to steady state. This provided more stable generator output and improved uniformity between desired or referenced signal (voltage) level and terminal signal (voltage) level. This showed that variation in transient time and settling time in the dynamic characteristics of a component in control loop can be corrected by adding a controller. In fact, the application of controller can provide uniformity during transition from transient state to steady-state in system's performance parameters. Generally, the PID+I-LQR provided the most efficient voltage profile performance at the generator output in terms of minimized oscillation (or improved stability) measured in terms of overshoot and peak value.

In order to further validate the ability of the designed PID-LQR based controllers in offering the most effective stable generator output terminal voltage, it was compared with other control strategies as shown in Figure 5 and Table 3. The comparison is based only on the generator terminal voltage profile given in per unit electrical input signal.

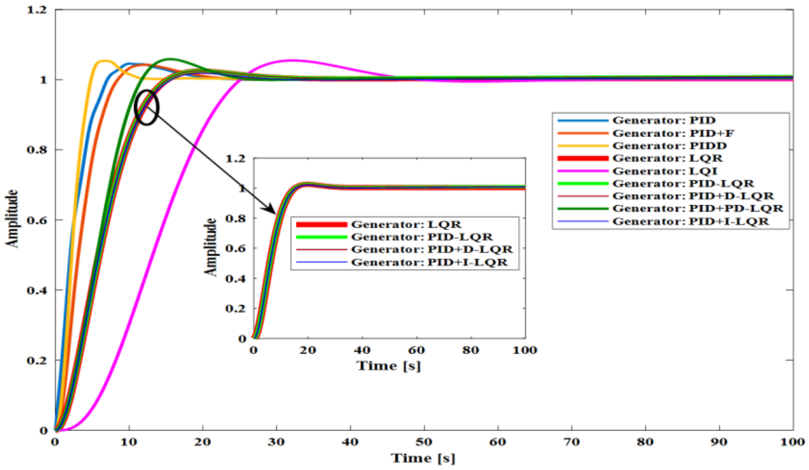

Figure 5 : Generator responses for AVR control systems

Table 3. Performance comparison of generator's output for different control systems

Controller	Peak value	Overshoot (%)	Rise time (s)	Transient time (s)	Settling time (s)	Steady-state error
PID	1.0458	4.5788	4.6483	16.5366	16.5366	0.00
PID+ F	1.0428	4.2765	5.2975	17.6066	17.6066	0.00
PIDD	1.0486	4.8533	3.1476	9.2119	9.2119	0.00
LQR	1.0245	2.1499	9.3820	21.3379	21.3379	0.00
PID-LQR	1.0255	1.6555	9.4982	14.4280	14.4280	0.01
LQI	1.0547	5.4693	15.1188	42.4085	42.4085	0.00
PID+D-LQR	1.0252	1.6197	9.5179	14.4685	14.4685	0.01
PID+PD-LQR	1.0585	5.3928	7.7181	21.0579	21.0579	0.04
PID+I-LQR	1.0182	1.1524	9.6233	14.7456	14.7456	0.01

The comparison plots in Figure 5 and Table 3 represent the response curves of PID, PID+F, and PIDD control system in addition to that of the designed LQR, LQI, PID-LQR, PID+D-LQR, PID+PD-LQR, and PID+I-LQR. It revealed that the introduction of the various controllers separately into the system improved the transient and steady-satte characteristics of the system. The control systems with LQR, PID-LQR, PID+D-LQR, and PID+I-LQR controllers yielded almost the same rise time and peak value (as shown in the sub-figure in Figure 5). In terms of stability, which is the main focus of this paper, the PID+I-LQR outperformed the other control systems. Generally, the use of PID based models to optimize the performance of LQR, has resulted in a system that offered smoother and more stable output for the synchronous generator.

CONCLUSION

This study has demonstrated the enhancement of synchronous generator exciter-based AVR control system stability through the application of a PID-LQR control technique. The results affirm the necessity of maintaining a steady terminal voltage level in power systems to ensure reliable load performance and prevent system-wide disturbances caused by voltage variability. Simulations revealed a delay in the exciter field's transition from dynamic to steady state, which was effectively addressed by incorporating the LQR technique. Further optimization with PID-based models significantly improved system stability, achieving near-zero overshoot values of 1.1524%, 1.6197%, and 1.6585% for PID+I-LQR, PID+D-LQR, and PID-LQR, respectively.

The findings highlight the scientific contribution of integrating PID with LQR to enhance voltage stability and reduce performance variability in power systems. This approach provides a more robust and responsive control strategy compared to conventional PID, PID+F, PIDD, and standalone LQR methods, thus offering practical value in the design of advanced excitation control systems.

Despite the improved stability and smooth response, the models exhibited relatively high rise and settling times. Future research should focus on leveraging swarm intelligence algorithms to optimize LQR or PID-LQR configurations, aiming to achieve faster dynamic responses and further enhance the control system’s performance.

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