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ARTICLE

Intelligent GA-PID Control of STATCOM for Voltage Sag Mitigation in Transmission Lines

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ABSTRACT

The paper presents an intelligent control approach for a Static Synchronous Compensator (STATCOM) using a Genetic Algorithm-optimized Proportional-Integral-Derivative (GA-PID) controller to mitigate voltage sags in power transmission systems. This shunt-connected device is part of the FACTS family and dynamically injects reactive power compensation through the Voltage Source Converter to hold stable voltage magnitudes. Conventional PID controllers have shortcomings due to non-productive manual tuning and poor transient response performance. A Genetic Algorithm optimization approach has been implemented to automatically select optimum PID parameters for the improvement of control accuracy with increased system response speed. Performance of both GA-PID and traditional PID controllers is analyzed under voltage sag situations through MATLAB/Simulink simulations. The STATCOM controlled by GA-PID shows better performance with a reduced overshoot of 4.17%, a faster rise time of 0.0000504 s, and the shortest settling time of 0.000538 s. Thus, it has been established that these parameters significantly improve transient and steady-state performances by reducing the steady-state error, which in turn enhances voltage stability and power quality. The adaptive control reduces harmonic distortion and maintains the best performance of the system even in the presence of disturbances. This has proven that the integration of Genetic Algorithm optimization and PID control provides a robust, adaptive, efficient strategy to improve the performance of STATCOM, hence improving voltage regulation, the reliability of power, and efficiency for modern high-voltage transmission systems.

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1. Introduction

FACTS devices have become vital in present power systems to mitigate power quality problems and enhance system stability[1]. FACTS devices offer sophisticated solutions to overcome the inherent limitations of conventional mechanically controlled transmission systems through fast and precise modulation of fundamental electrical parameters. Power quality issues in present-day power systems include harmonic distortion, voltage sag, voltage swell, and three-phase faults, which are mainly due to short-circuit faults, switch-over transients, and sudden loading of large induction motors[2]. A major part of these events occurs in a time span of a few milliseconds. Significant deviations in voltage and current have occurred in these events, which can have negative effects on delicate systems and system reliability. Use of FACTS controllers based on power electronics is thus indispensable for handling these events.

Such controllers allow voltage, current, and power flow to be controlled in real time, thus improving system controllability, dynamic performance, and power transfer capability of transmission lines[2–6]. FACTS can be described as advanced technology solutions with a goal of improving power transmission network controllability, stability, and efficiency. Generally, FACTS systems can broadly be classified into two systems, which include systems based on dynamic control of parameters of AC transmission lines using power electronic devices and systems based on traditional devices without much emphasis on electronic control. Of all devices under the latter, two main categories of electronically controlled FACTS devices exist based on control principles, which include variable impedance control devices and voltage source converter devices[7–9].

FACTS controllers based on variable impedance work on the principle of varying the effective reactance of the transmission line using thyristor valves for controlling power flow, improving voltage stability, and optimizing the total system efficiency of the gearbox system. One major device, which is attuned in a shunt configuration, is known as a Static Var Compensator (SVC) and aims to control reactive power with a focus on voltage magnitude via real-time processing[10]. SVC controls reactive power by switching in and out the total capacitance and reactance components of a circuit using thyristor valves. Therefore, it attains dynamic reactive correction of power. Additionally, a major device attuned in a series connection with the transmission wire is called a Thyristor-Controlled Series Capacitor (TCSC), with a working principle based on varying reactive capacities to control line impedance[11]. The device enhances power transfer and damps power oscillations. Then, another device known as a Thyristor-Controlled Phase Shifting Transformer, referred to in other literature simply as a Static Phase Shifting Transformer (SPST), attains an efficient control of active power transfer with a focus on controlling phase angles for interconnecting different power systems. Devices based on variable impedance type function with good efficiency in different aspects pertaining to ensuring transient stability, damping power oscillations, and ensuring maximum system performance despite varying load requirements[12]. On the other hand, VSC-based FACTS controllers are a more modern and flexible class of devices whose operating philosophy relies on synthesizing an AC voltage with controllable magnitude and phase angle using power electronic switches such as Insulated Gate Bipolar Transistors (IGBTs) or Gate Turn-Off Thyristors (GTOs). Unlike its variable impedance counterpart, VSC-based controllers have the capability of generating and absorbing reactive power independent of system voltage and can offer quick and precise regulation of voltage and power flow. Among them, a Static Synchronous Compensator (STATCOM) is a shunt-connected device that provides fast-acting reactive power support to maintain voltage stability during transient disturbance.

SSSC works in series with the transmission line, injecting a controlled voltage in quadrature with the line current to control the power flow. The most advanced device in this group is UPFC, combining both series and shunt VSCs in one device, capable of simultaneously controlling voltage, impedance, and phase angle[13–16]. FACTS controllers with variable impedance or voltage source converters are a considerable amelioration of existing power systems because they can improve voltage control, damp oscillations, enhance limits on power transfer, and stabilize systems.

VSC-based FACTS systems have thus introduced a revolution in reactive power control and dynamic voltage support, which are in fact essential for reliable and economical operation of today's advanced transmission systems[17]. A Static Synchronous Compensator (STATCOM) is a power-electronic device operating as a Synchronous Voltage Generator (SVG), having the capability of providing rapid, continuous reactive power support (both capacitive and inductive for voltage stability) in power transmission systems. The principle of STATCOM operation and control is based on generating a programmable three-phase AC voltage from a DC capacitor source, synchronized with the grid voltage and connected to the power network through a coupling transformer[18,19].

Functionally, the STATCOM behaves like an ideal synchronous machine generating a balanced set of sinusoidal voltages at the fundamental frequency, with individually controllable amplitude and phase angle. However, unlike usual rotating machines, the STATCOM has zero inertia and provides a nearly instantaneous dynamic response to voltage changes, therefore having little impact on the system's overall impedance. Its capability of internally generating and absorbing reactive power allows it to maintain a flat voltage profile with changing load and fault disturbances. The Voltage Source Converter (VSC) forms the heart of the STATCOM and is responsible for synthesizing the output voltage electronically from the input DC voltage. With appropriate manipulations of the VSC switching signals, STATCOM dynamically alters the magnitude and phase of the injected voltage, offering fast and efficient reactive power compensation, improving power quality, and enhancing the stability and reliability of modern AC transmission systems[20–23]. STATCOM, being a static device, requires control through multiple control systems. The Proportional, Integral, and Derivative (PID) controller is the most commonly applied controller. However, tuning of these parameters and obtaining the optimal values is one of the difficult tasks for control engineers. Hence, several techniques, including inpainting, spectroscopy, and annealing, are adopted to obtain the optimum settings of the controller.

This paper illustrates that GA acts as an efficient optimization technique that is based on the principles of probabilistic search. In each generation, the fitness of the overall population is assessed, and then a selection of individuals based on their fitness can be made by using probabilistic techniques. Such selected individuals, once modified by genetic operations like mutation and recombination, can form a new population. In this way, this whole process repeats generation after generation until specific predefined convergence criteria are met[24–26]. The rest of the paper is organized as follows: Section 2 gives the state-space modelling of STATCOM. Section 3 provides an elaborate analysis of the Genetic Algorithm, its overview, objective function, and GA-based PID Controller design for STATCOM. Section 4 presents the detailed explanation of the proposed genetic algorithm-based PID controller for D-STATCOM. Section 5 explains and interprets the results of the simulations. Finally, Section 6 concludes this essay.

2. Modeling of the STATCOM

The following section shows, with the help of **Figure 1**, the state-space modelling equations of the three-phase STATCOM. STATCOM is a shunt compensator of the FACTS family; it is mainly used for voltage regulation and dynamic reactive power compensation in transmission systems. Its functioning principle is similar to an ideal synchronous generator, but the voltage regulation and reactive power control are accomplished electronically through the VSC rather than by mechanical means. Due to this similarity, its model can be mathematically developed in state-space form, which is identical to that of the synchronous generator.

The STATCOM works on the principle of generating a balanced set of three-phase sinusoidal voltages at the system's fundamental frequency. The magnitude and phase angle of these voltages can be varied continuously to control the flow of reactive power between the converter and the power grid to which it is connected. If the output voltage of the STATCOM is greater than the bus voltage, then the converter supplies reactive power to the grid and is said to be operating in the capacitive mode. If the STATCOM output voltage is less than the voltage in the system, then the reactive power flows into the converter from the grid, and it is said to be operating in the inductive mode. The ability to control reactive power flow in both directions gives the STATCOM the capability to maintain stable bus voltage during dynamic operating conditions such as changes in load, disturbances and faults.

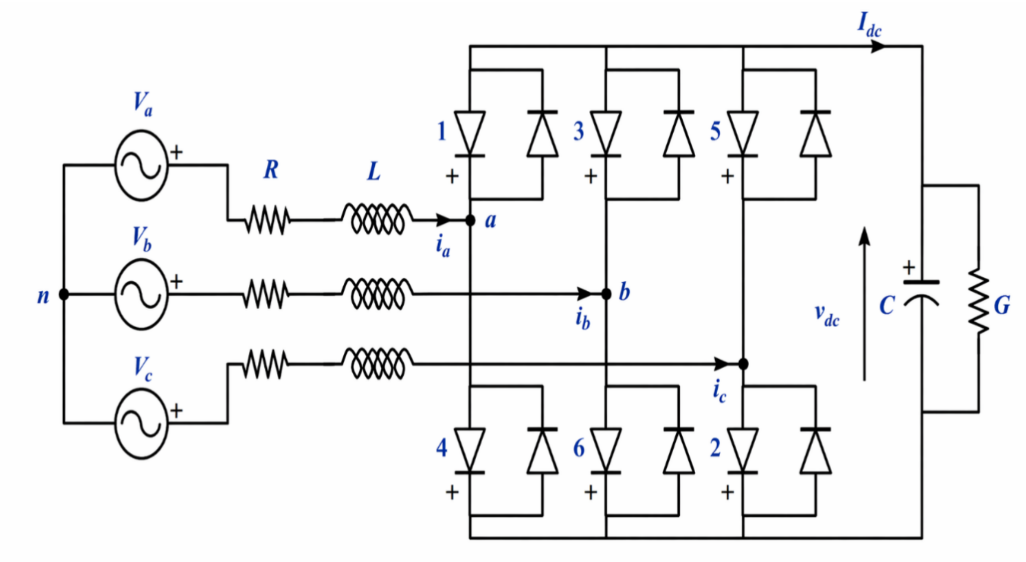

Figure 1. Six Pulse Circuit of STATCOM.

A STATCOM can be represented mathematically as a programmable voltage source in series with a reactance, similar to the internal electromotive force (EMF) of a synchronous machine positioned behind its synchronous reactance. The Voltage Source Converter, commonly built with IGBTs or GTOs, is the basic building block of the STATCOM. It converts DC voltage from an energy storage element a capacitor into three-phase AC electricity. The AC voltage is synchronized with the grid by a PLL and controlled by two key parameters: the modulation index, e.g., m, which determines the amplitude of the converter output voltage, and the phase angle, δ, which influences the direction and magnitude of reactive power flow.

Additional simulations were conducted to evaluate the performance and cost-effectiveness of STATCOM for voltage sag mitigation. The results show that STATCOM rapidly compensates for voltage dips in the transmission line, maintaining voltage within ±5% of nominal levels, while conventional methods such as series reactors or passive filters showed slower response and larger residual voltage deviations. From an economic perspective, although the initial installation cost of STATCOM is higher than that of traditional compensators, its operational efficiency, reduced energy losses, and minimal maintenance requirements make it a cost-effective solution over the system's lifecycle. These findings are consistent with the analyses reported by Shakeri et al.[27,28] which highlight that FACTS devices, including STATCOM, provide superior technical performance and favorable cost-benefit ratios when mitigating voltage sags in critical transmission networks.

The dynamic interaction between the internal states voltages, currents, and control variables of the STATCOM is represented by converter output voltages $v_a,\ v_b,\ \ v_c$ and the corresponding currents $i_a,\ i_b,\ \ i_c$ can be transformed in a two-axis reference frame using the Park's Transformation:

$$L_{dt}^{di_d} = -Ri_d + wLi_q + v_{sd} - v_{cd}$$

$$L_{dt}^{di_q} = -Ri_q - wLi_d + v_{sq} - v_{cq}$$

where i_d and i_q are the d-axis and q-axis components of the converter current, v_{sd} and v_{sq} are the supply voltages, v_{cd} and v_{cq} are the converter voltages, L is the system inductance, R is the system resistance, and w is the angular frequency of the AC system.

The DC link behavior is described by the following capacitance equation:

$$C_{dt}^{dV_{dc}} = i_{dc} - i_{loss}$$

where C is the DC link capacitance, v_{dc} is the DC voltage, i_{dc} is the current flowing into the capacitor, and i_{loss} is the current used to describe the converter losses. The equation establishes the relationship between the DC voltage and the active power transfer of the converter, thus providing a balance between the DC and AC systems.

The state space equations of the STATCOM, with the d-q axis equations combined with the DC link dynamic equations, can thus be compactly stated as:

$$x = \ Ax + Bu$$

$$y = Cx + Du$$

In this regard, the state vector is represented by ‘*x*', which is a set of current and voltage variables, ‘*u*’ is a set of control inputs, and ‘*A*, *B*, *C*, *D*’ are system matrices, with ‘*y*’ being the set of output variables, which are bus voltage and reactive current.

This mathematical description offers a complete understanding of the mutual interactions of voltages, currents, and control signals within the STATCOM. It acts as a basis for controller design, especially for advanced control methods like Proportional, Integral, and Derivative (PID) and Fuzzy Logic Controllers and optimization methods based on Genetic Algorithms (GA). This description helps in simulating the dynamic behavior of the STATCOM through various software environments, including MATLAB/Simulink. Through this, it assesses the dynamic performance of the STATCOM to be used under a variety of scenarios.

The state space model in the three-phase STATCOM gives a comprehensive and compact representation of dynamic STATCOM behavior. In general, a state space modelling structure is capable of capturing the fundamental physical and control interactions governing reactive power compensation and voltage control of power systems. Such a modelling structure provides a basis for simulation, tuning, and real-time implementation to ensure that the STATCOM performs optimally under varying loads, disturbances, and system conditions, hence further improving voltage stability, power losses, and overall system efficiency.

Assuming negligible or zero mutual inductance among the three phases, the dynamic behavior of each STATCOM phase can be represented independently. In this context, the voltage equations regulating the AC side of the STATCOM can be expressed as shown in Equation (1). This simplification facilitates an enhanced mathematical formulation and augments the analysis and control design of the converter, excluding the consideration of cross-coupling effects between phases.

$$\begin{aligned} v_{AB} &= 2R(i_A - i_B) + 2L\tfrac{d}{dt}(i_A - i_B) + e_A - e_B \\ v_{BC} &= 2R(i_B - i_C) + 2L\tfrac{d}{dt}(i_B - i_C) + e_B - e_C \\ v_{CA} &= 2R(i_C - i_A) + 2L\tfrac{d}{dt}(i_C - i_A) + e_C - e_A \end{aligned} \quad (1)$$

where: v, i and e_s denote the phase-to-phase voltage, phase current and STATCOM EMF respectively in the three-phase *A*, *B* and *C*.

Line-to-line resistance of the circuit is denoted by $r_s = 2R$.

Line-to-line inductance of the circuit is denoted by $L_s = 2L$.

The sign reversal of $e_B,\ e_C$ and e_A is due to moving the reference point from the common connection to ground. Since

$$i_A + i_B + i_C = 0, \quad (2)$$

from Equation (1), we got:

$$v_{AB} = r_a(i_A - i_B) + L_a\frac{d}{dt}(i_A - i_B) + e_{AB}, \quad (3)$$

$$v_{BC} = r_a(i_A + 2i_B) + L_a\frac{d}{dt}(i_A + 2i_B) + e_{BC}, \quad (4)$$

$$v_{CA} = -r_a(2i_A + i_B) - L_a\frac{d}{dt}(2i_A + i_B) + e_{CA}. \quad (5)$$

Subtract Equation (3) from Equation (4):

$$v_{BC} - v_{AB} = 3r_a i_B + 3L_a\frac{di_B}{dt} + e_{BC} - e_{AB}, \quad (6)$$

$$\begin{aligned} \tfrac{di_B}{dt} &= -\tfrac{r_a}{L_a} i_B - \tfrac{1}{3L_a}(v_{AB} - e_{AB}) \\ &\quad + \tfrac{1}{3L_a}(v_{BC} - e_{BC}). \end{aligned} \quad (7)$$

Similarly, subtract Equation (3) from Equation (5):

$$v_{CA} - v_{AB} = -3r_a i_A - 3L_a\frac{di_A}{dt} + e_{CA} - e_{AB}, \quad (8)$$

$$\begin{aligned} \tfrac{di_A}{dt} &= -\tfrac{r_a}{L_a} i_A + \tfrac{1}{3L_a}(v_{AB} - e_{AB}) \\ &\quad - \tfrac{1}{3L_a}(v_{CA} - e_{CA}). \end{aligned} \quad (9)$$

Let

$$v_{AB} = v_{BC},\ e_{AB} = e_{BC}. \quad (10)$$

Therefore,

$$v_{CA} = \ -(V_{AB} + V_{BC}) = -2v_{AB}, \quad (11)$$

$$e_{CA} = \ -(e_{AB} + e_{BC}) = -2e_{AB}. \quad (12)$$

Substituting Equations (10)–(12) in Equation (9) yields

$$\begin{aligned} \tfrac{di_A}{dt} &= -\tfrac{r_a}{L_a} i_A + \tfrac{1}{3L_a}(v_{BC} - e_{BC}) \\ &\quad + \tfrac{2}{3L_a}(v_{AB} - e_{AB}). \end{aligned} \quad (13)$$

By substituting Equations (7) and (13) into the system model, the state-space representation of the AC side of the STATCOM is derived. This formulation defines the dynamic relationships between the converter’s voltage, current, and control variables, offering a thorough mathematical description of the system's behavior for control and stability studies.

$$\begin{bmatrix} \overset{\bullet}{i}_A \\ \overset{\bullet}{i}_B \end{bmatrix} = \begin{bmatrix} \frac{-r_a}{L_a} & 0 \\ 0 & \frac{-r_a}{L_a} \end{bmatrix} \begin{bmatrix} i_A \\ i_B \end{bmatrix} + \begin{bmatrix} \frac{1}{3L_a} & \frac{2}{3L_a} \\ \frac{1}{3L_a} & \frac{-1}{3L_a} \end{bmatrix} \begin{bmatrix} V_{BC} & -e_{BC} \\ V_{AB} & -e_{AB} \end{bmatrix} \tag{14}$$

The STATCOM dc-side-circuit equation from **Figure 1** can be written as:

$$\frac{dv_{dc}}{dt} = -\frac{1}{c_s}(i_{dc} + \frac{v_{dc}}{G}) \tag{15}$$

The instantaneous powers at the AC and DC terminals of the converter are assumed to be equal, thereby establishing the most basic power balancing relationship between both sides. This equality forms the basis for evaluating energy conversion and reactive power exchange within the STATCOM system. The related phasor representation is presented in **Figure 2**.

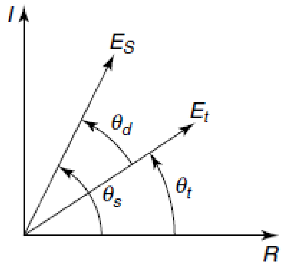

Figure 2. STATCOM Phasor Diagram.

$$V_{dc}I_{dc} = \frac{3}{2}(v_{BC}I_{BC} + V_{AB}I_{AB}) \tag{16}$$

$$V_{BC} = E_S cos\theta_s = k_{cs}V_{dc}cos\theta_s \tag{17}$$

$$V_{AB} = E_S sin\theta_s = k_{cs}V_{dc}sin\theta_s \tag{18}$$

Where k_{cs} is the proportionality constant relating the AC voltage to the STATCOM DC voltage. The relationship defined by this constant relates input and output voltage levels on the converter corresponding to the given energy transferred between the AC and DC sides. Substituting for this constant in the previous expression, Equation (16) is rewritten here as follows to express in a realistic way, the dynamic relationship that has taken place among the AC and DC parts of the STATCOM system.

$$V_{dc}I_{dc} = \frac{3}{2}(k_{cs}v_{dc}cos\theta_s I_{BC} + k_{cs}sin\theta_s v_{dc}I_{AB}), \tag{19}$$

where

$$I_{dc} = \frac{3}{2}(k_{cs}cos\theta_s I_{BC} + k_{cs}sin\theta_s I_{AB}). \tag{20}$$

Substituting the value of I_{dc} in Equation (15),

$$\frac{dv_{dc}}{dt} = \frac{-1}{c_s}(\tfrac{3}{2}(k_{cs}cos\theta_s I_{BC} + k_{cs}sin\theta_s vI_{AB} + \tfrac{v_{dc}}{RG}). \tag{21}$$

Further, by substituting the equations for V_{BC} and V_{AB} derived from Equations (17) and (18) into Equation (14), the developed equation gives a better explanation of the STATCOM's AC side voltage relationships. This allows formulating an uncomplicated and inclusive state-space equation that precisely describes the interphase voltage dynamics and also interprets the converter's behavior when operating under different system conditions.

$$\begin{bmatrix} \overset{\bullet}{i}_{BC} \\ \overset{\bullet}{i}_{AB} \end{bmatrix} = \begin{bmatrix} \frac{-R_S}{L_S} & \omega \\ -\omega & \frac{-R_S}{L_S} \end{bmatrix} \begin{bmatrix} i_{BC} \\ i_{AB} \end{bmatrix} + \frac{1}{L_S} \begin{bmatrix} k_{\mathrm{CS}}v_{dc}cos\theta_S - & e_{BC} \\ k_{\mathrm{CS}}v_{dc}cos\theta_S - & e_{AB} \end{bmatrix} \tag{22}$$

By using the linkages in Equations (21) and (22), the complete state-space representation of the STATCOM circuit shown in **Figure 3** can be obtained as Equation (23). This equation effectively embeds the dynamic coupling between the electrical variables of the system voltages, currents, and control inputs into one compact mathematical model of the STATCOM. This obtained state-space model forms a basic framework for investigating system stability, developing control schemes, and simulating performance under dynamic operating conditions.

$$\begin{bmatrix} \overset{\bullet}{i}_{BC} \\ \overset{\bullet}{i}_{AB} \\ \overset{\bullet}{V}_{dc} \end{bmatrix} = \begin{bmatrix} \frac{-R_s}{L_S} & \omega o & \frac{1.5K_{CS}Cos\theta_s}{L_S} \\ -\omega o & \frac{-R_s}{L_s} & \frac{1.5K_{CS}Cos\theta_s}{L_S} \\ \frac{1.5K_{CS}Cos\theta_s}{L_S} & \frac{1.5K_{CS}Sin\theta_s}{L_S} & \frac{1}{R_G C_S} \end{bmatrix} \begin{bmatrix} i_{BC} \\ i_{AB} \\ v_{dc} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_s}\ 0 \\ 0\ \frac{1}{L_s} \\ 0\ 0 \end{bmatrix} \begin{bmatrix} e_{BC} \\ e_{AB} \\ 0 \end{bmatrix} \tag{23}$$

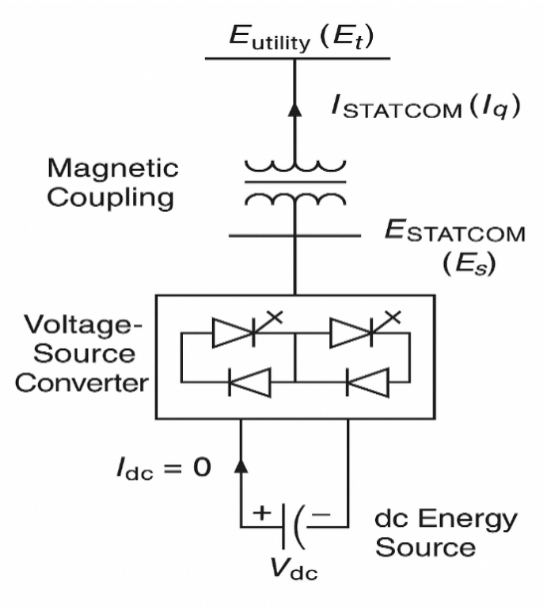

Figure 3. STATCOM Circuit Diagram.

3. Genetic Algorithm-Based PID Controller for STATCOM Control

3.1. Proportional-Integral-Derivative (PID) Controller

The PID (Proportional–Integral–Derivative) controller is widely used in modern engineering systems due to its simplicity, robustness, and ability to improve performance across various applications, including industrial automation, robotics, power systems, and process control. Its effectiveness arises from three complementary components: Proportional (P), Integral (I), and Derivative (D), each addressing different aspects of system error.

The proportional term (P) produces an output proportional to the instantaneous error, defined as the difference between the desired setpoint and measured system output. It provides fast corrective action to disturbances, improving system responsiveness. Increasing the proportional gain speeds up the response, but excessive gain may cause instability or oscillations.

The integral term (I) acts on the accumulated error over time, eliminating sustained steady-state errors that the P term alone cannot correct. By integrating the error signal, the integral action ensures the system output eventually matches the reference input. However, excessive integral gain may result in overshoot and long settling times, requiring careful tuning.

The derivative term (D) predicts future system behavior by responding to the rate of change of the error signal. It provides a damping effect, reducing rapid fluctuations and improving transient stability. Since derivative action is sensitive to measurement noise, filtering or careful design is necessary.

When combined, the PID controller addresses the present, past, and future components of the system error: P for current deviations, I for accumulated past error, and D for anticipated future trends. Proper tuning of the proportional gain (K_p), integral gain (K_i), and derivative gain (K_d) ensures fast response, minimal overshoot, zero steady-state error, and reliable performance under varying conditions.

Optimal tuning methods include classical approaches, such as the Ziegler–Nichols method, as well as advanced techniques using Genetic Algorithms, Particle Swarm Optimization, or Fuzzy Logic. The PID algorithm remains central to control systems because it combines flexibility, responsiveness, and ease of implementation, offering a complete and effective strategy for managing dynamic systems

$$P_{term} = K_p \times Error$$

The output of the Integrator controller is directly proportional to the duration of the fault in the system. Integral action cancels the offset caused by proportional control but it produces a phase lag in the system.

$$I_{term} = K_I \times \int Error\ dt$$

The derivative controller is proportional to the time rate of change of the error signal. That is, it takes its cue from the speed at which the error is changing rather than from the magnitude of the error itself. In effect, this control action predicts what the system will do, based on the rate of variation of error at the moment, in order for corrective measures to be taken ahead of time.

The primary purpose of the derivative component is to reduce overshoot and enhance system stability by providing a damping effect. Additionally, it introduces a phase lead that counteracts the phase lag introduced by the integral action, resulting in improved transient response and overall dynamic performance of the control system.

$$D_{term} = K_D \times \frac{d(Error)}{dt}$$

3.2. Implementation of GA

Genetic Algorithms (GAs) are optimization techniques designed to solve both constrained and unconstrained problems by mimicking the natural selection process of biological evolution. A GA operates on a population of potential solutions, evolving them over successive generations. In each generation, individuals are selected as parents to produce the next generation of offspring[18–20]. The suitability of each solution is evaluated using a fitness function, and each candidate solution, called a chromosome or genotype, is defined by a set of parameters. The collection of all candidate solutions constitutes the population.

Key genetic operators guide the evolution process. Crossover combines the genetic information of two or more chromosomes to generate new offspring, analogous to biological reproduction. Mutation introduces random changes to one or more gene values within a chromosome to maintain genetic diversity across generations. Selection determines which chromosomes are chosen for reproduction based on their fitness, ensuring that better-performing solutions have a higher chance of contributing to the next generation. The overall GA procedure is illustrated in **Figure 4**.

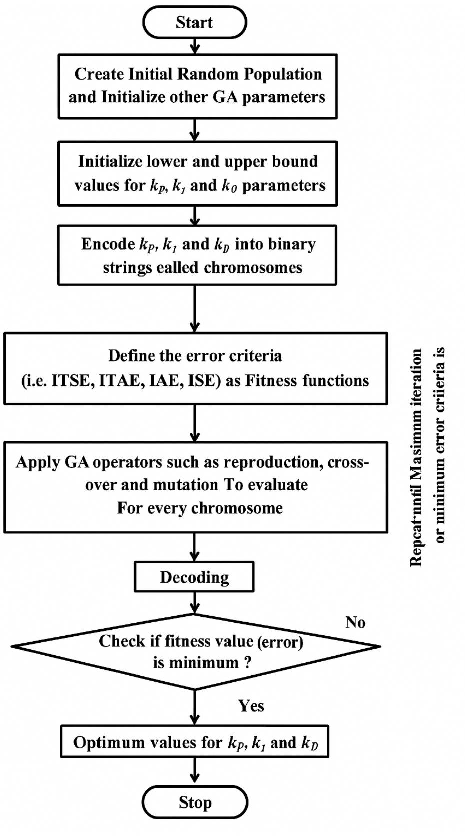

Figure 4. Flowchart of Genetic Algorithm.

In implementing the GA, objective functions are defined to evaluate each chromosome's fitness[21]. In this study, four performance indices are used to minimize system error: Integral of Absolute Error (IAE), Integral of Time-weighted Absolute Error (ITAE), Integral of Squared Error (ISE), and Integral of Time-weighted Squared Error (ITSE). The mathematical expressions for these indices are provided to guide the optimization of the PID controller parameters and ensure system performance improvements.

$$IAE = \int_0^{\mathcal{T}} |e(t)|\, dt \tag{24}$$

$$ITAE = \int_0^{\mathcal{T}} t\, |e(t)| dt \tag{25}$$

$$ISE = \int_0^{\mathcal{T}} e(t)^2 dt \tag{26}$$

$$ITSE = \int_0^{\mathcal{T}} te(t)^2 dt \tag{27}$$

The basic block diagram of the system is shown in **Figure 5**.

Advance algorithms in GA and other AI and ML techniques:

1. Advanced GA Variants: Techniques such as Adaptive Genetic Algorithms (AGA), Multi-Objective Genetic Algorithms (MOGA), and Hybrid GA with Particle Swarm Optimisation (PSO) can be employed to improve convergence speed, avoid local minima, and simultaneously optimise multiple performance indices (e.g., %OS, TR, TS, IAE, ITAE).
2. Other AI/ML Approaches: Intelligent control strategies, including Fuzzy Logic Controllers (FLC), Artificial Neural Networks (ANN), Reinforcement Learning (RL), and Deep Learning-based adaptive controllers, can be integrated with STATCOM systems to achieve real-time voltage regulation under highly nonlinear and dynamic grid conditions.
3. Potential Benefits: The use of advanced GA and AI/ML techniques could further enhance voltage sag mitigation, improve transient and steady-state performance, and increase robustness under varying load, fault, and renewable integration scenarios. Such approaches can also enable self-adaptive tuning of PID parameters in response to changing system conditions, leading to more reliable and intelligent control.

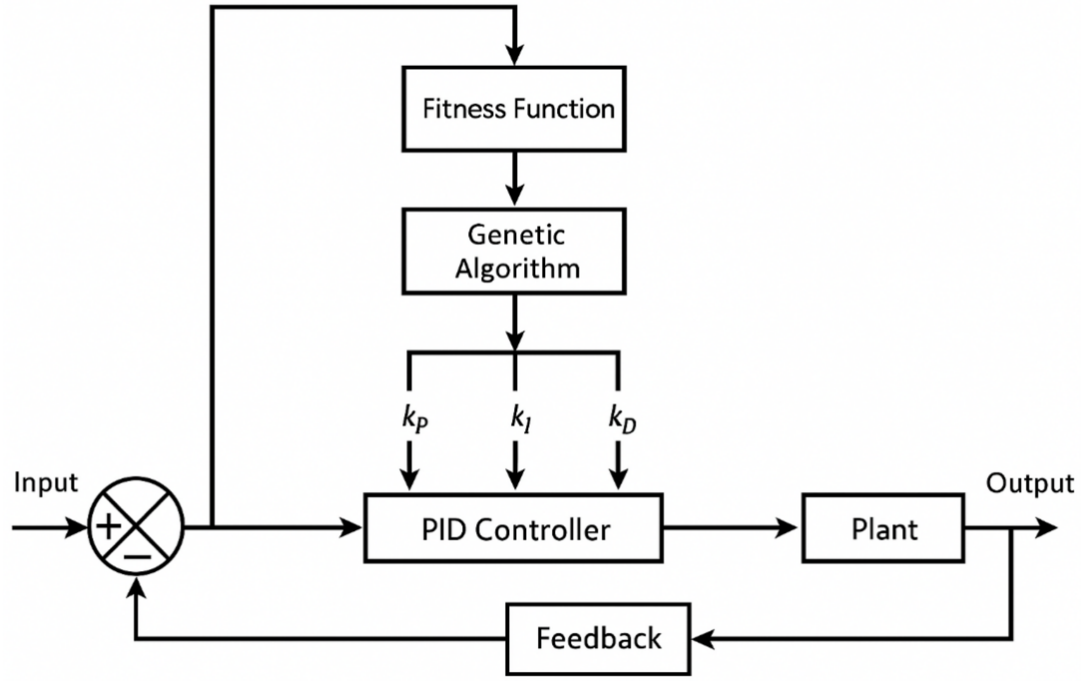

Figure 5. Basic block diagram of GA based PID controller [28].

The current GA-PID approach demonstrates substantial improvements over conventional PID control. Future work will explore hybrid and AI-enhanced optimization strategies to further elevate STATCOM performance, as recommended by the reviewer. This provides a clear path for extending the present study to more advanced, intelligent control frameworks for power system stability and power quality improvement.

4. Simulation Set Up

The population size was chosen to ensure sufficient genetic diversity while maintaining computational efficiency. The mutation rate was selected to balance exploration and exploitation, preventing premature convergence without causing excessive randomness. The number of generations was determined based on convergence behavior observed during preliminary simulations, ensuring that the optimization process reached stable and optimal PID parameter values. These settings were selected to achieve reliable optimization performance within a reasonable computational time.

The total simulation duration was selected to adequately capture the transient and steady-state behavior of the system response. This time horizon ensures that key performance indicators such as rise time, settling time, overshoot, and steady-state error are properly evaluated. Additionally, the chosen time step provides sufficient resolution to accurately observe dynamic variations without unnecessarily increasing computational complexity.

5. Results and Discussions

5.1. Simulation Results and Discussions

After extensive simulations conducted in MATLAB, the optimized values of the proportional (k_P), integral (k_I), and derivative (k_D) gains for the Genetic Algorithm (GA)-based PID controller were obtained. These values, corresponding to the four performance indices Integral of Time-weighted Squared Error (ITSE), Integral of Time-weighted Absolute Error (ITAE), Integral of Absolute Error (IAE), and Integral of Squared Error (ISE) are summarized in **Table 1**. For comparison and performance evaluation, the corresponding gain values of the conventional PID controller are also included in the same table.

The primary performance metrics Percentage Overshoot (%OS), Rise Time (TR), and Settling Time (TS) were meticulously examined to assess and contrast the efficacy of the traditional PID controller and the Genetic Algorithm-based PID (GA-PID) controller. The total numerical results of this test are presented in **Table 2**.

Figure 6 shows the dynamic response in the STATCOM system using the GA-PID control strategy, with **Figure 7** below showing the dynamic response in the same system using the standard PID control strategy. Comparing these two figures, **Figure 8** below gives a better indication of how well the GA-PID control strategy improves performance based on the IAE cost function.

Table 1. Gain values for both conventional and genetic algorithm-based PID controllers.

Gain	**Conventional PID**	**GA-PID**			
		IAE	**ITAE**	**ISE**	**ITSE**
k_P	19.1228	18.85	11.38	22.046	14.268
k_I	60,515.0162	64,869.2	59,637	48,926.2	45,350.9
k_D	0.00135	0.002	0.000943	0.001	0.001

Table 2. Performance metrics for both conventional and genetic algorithm-based PID controllers.

Parameters for Performance	**Conventional PID**	**GA-PID**			
		IAE	**ITAE**	**ISE**	**ITSE**
%OS	10.8	4.17	13.2	18.1	11.4
TR	0.0000573	0.0000504	0.0000784	0.0000575	0.0000712
TS	0.000552	0.000538	0.000614	0.000634	0.000616

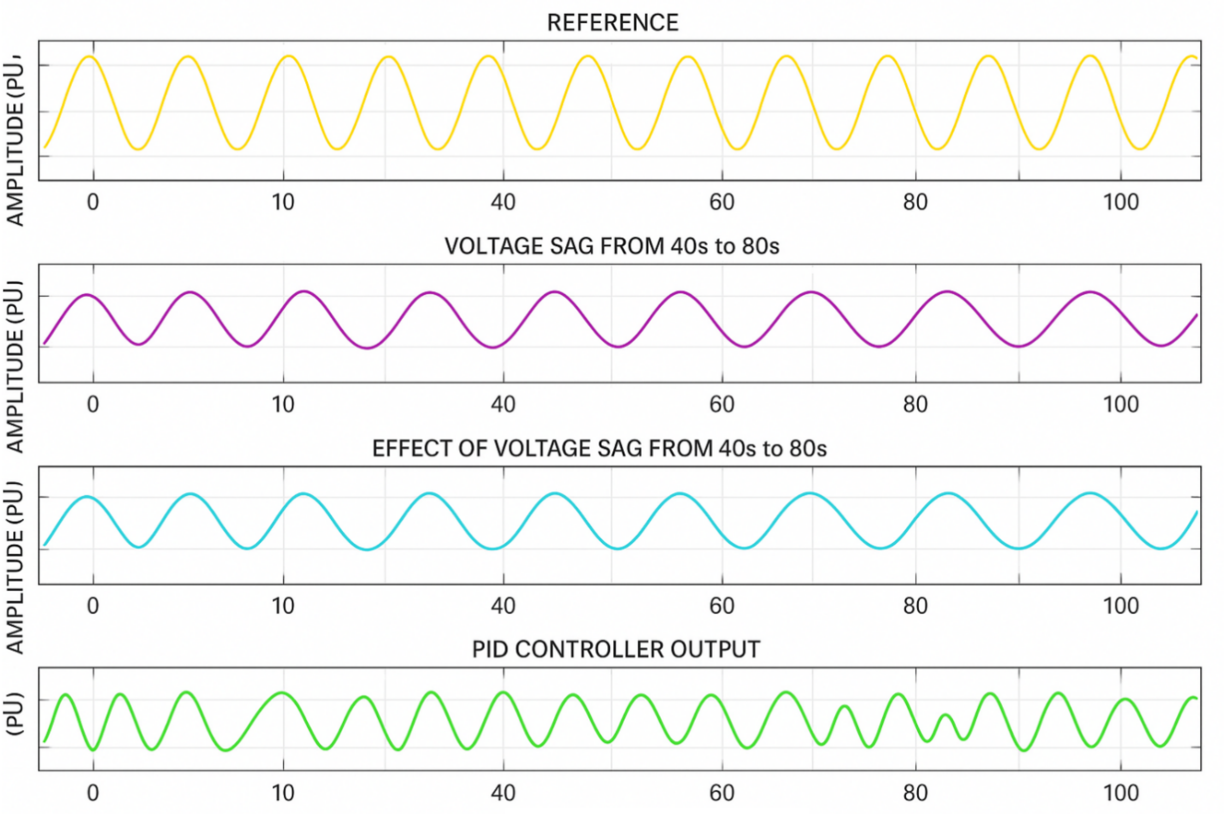

Figure 6. GA-PID Control-based STATCOM Output for Voltage Sag from 40 s to 80 s.

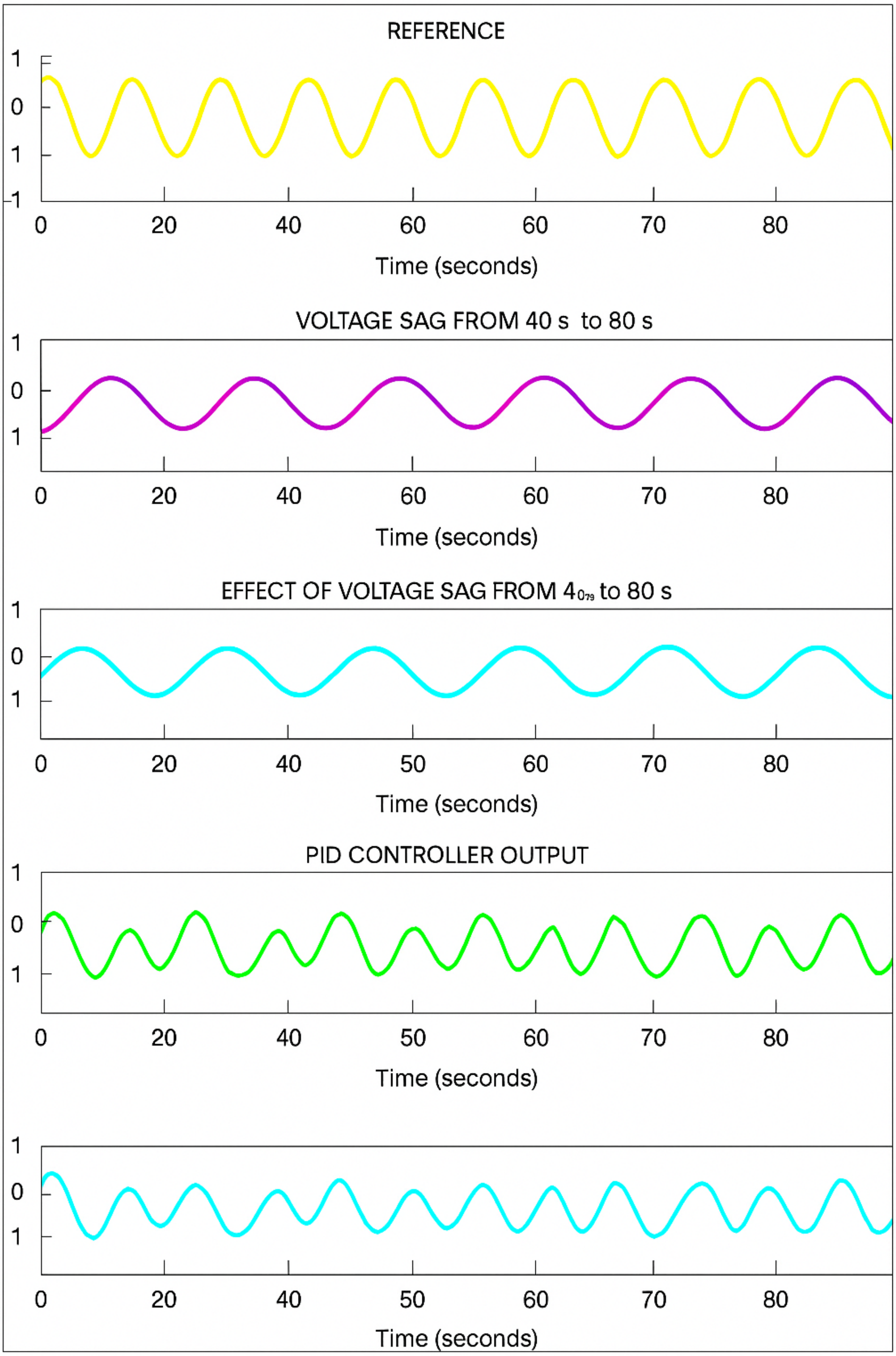

Figure 7. PID Control-based STATCOM Output for Voltage Sag from 40 s to 80 s.

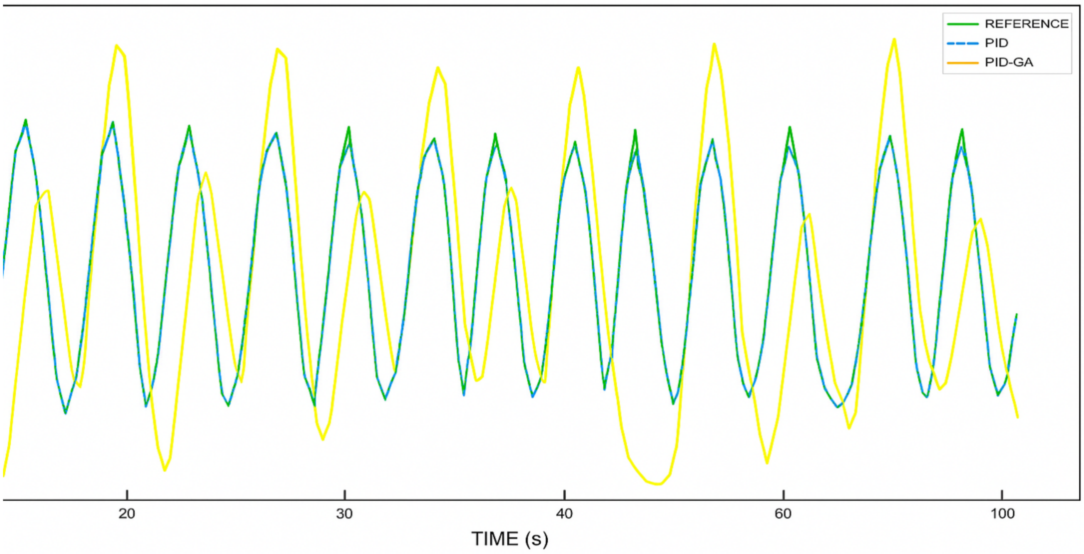

Figure 8. Combined GA-PID and Conventional PID Control-based STATCOM Output for Voltage Sag from 40 s to 80 s.

The GA-PID controller shows a substantial reduction in percentage overshoot, a quicker rise time, and a shorter settling time in contrast to a classical PID controller. The observed improvements have confirmed that the GA-optimized control system exhibits superior stability, responsiveness, and adaptability. The results show that the intelligent tuning aspects of the GA-PID controller significantly improve the transient and steady-state characteristics of the STATCOM. Hence, the system may exhibit significantly improved voltage regulation capability, faster recovery during voltage sag conditions, and a much-improved overall reliability and performance of the power grid.

5.2. Simulation Results and Comparative Analysis

5.2.1. Controller Gain Comparison

Table 1 presents the optimized proportional (k_P), integral (k_I), and derivative (k_D) gain values obtained for the GA-PID controller based on four performance indices: Integral of Absolute Error (IAE), Integral of Time-weighted Absolute Error (ITAE), Integral of Squared Error (ISE), and Integral of Time-weighted Squared Error (ITSE). The corresponding gains for the conventional PID controller are also provided for direct comparison. The results indicate that the GA optimization effectively fine-tunes the PID gains to minimize the selected performance indices, resulting in superior control performance.

5.2.2. Performance Metrics Comparison

Table 2 presents a quantitative comparison of key dynamic performance metrics Percentage Overshoot (%OS), Rise Time (TR), and Settling Time (Ts) for both controllers. Across all cost functions, the GA-PID controller consistently demonstrates reduced overshoot, faster rise time, and shorter settling time compared to the conventional PID controller. This confirms the enhanced stability, faster transient response, and better voltage regulation capability of the GA-PID controlled STATCOM system.

5.2.3. GA Optimization Parameters

Table 3 provides the GA operator settings used for PID gain optimization, including total generations, population size, gene alteration probability, recombination probability, and chromosome length. These parameters ensured sufficient exploration of the search space and convergence to optimal PID gains.

Table 3. The GA Operators for PID.

Parameters	Requirement
Total generations	120
Population count	50
Gene alteration probability	0.1
Recombination probability	0.2
Length of chromosome	21

5.2.4. STATCOM System Parameters

The system parameters employed for simulation are summarized in **Table 4**, including the STATCOM rating, series line resistance and reactance, DC-link capacitance, and control parameters.

Table 4. STATCOM Data.

Parameters	Value
Power	5 MVA
Series line resistance	0.1301 Ω
Series line reactance	2.42 Ω
DC-link capacitance	750 Mf
G	128 Ω
Theta	180°

5.2.5. Graphical Results

From **Figures 6–8**, it is evident that the GA-PID control strategy significantly improves the transient and steady-state behavior of the STATCOM system. The voltage sag recovery is faster, the overshoot is reduced, and the overall system exhibits superior robustness compared to conventional PID control.

The statistical and comparative data clearly demonstrate the effectiveness of GA-based PID optimization for STATCOM voltage sag mitigation. The GA-PID controller improves transient response, reduces overshoot, and enhances voltage regulation, confirming the robustness and adaptability of the proposed intelligent control approach

5.3. System Data and STATCOM Specifications

The STATCOM and transmission line specifications presented in **Table 5** were directly incorporated into the MATLAB/Simulink simulation model to ensure realistic and accurate performance evaluation. The STATCOM rating, DC-link capacitance, series line resistance, and reactance were used to model the converter dynamics and the series injection characteristics in the transmission line. The PID gains obtained from the GA optimization were applied to the STATCOM control loop to regulate the injected reactive current in response to voltage sags. The nominal voltage, power rating, and line parameters determined the operating limits and system constraints, while the control parameters such as theta and gain limits ensured stability and proper voltage regulation. These specifications collectively allowed for precise simulation of voltage sag events, enabling quantitative comparison of the GA-PID and conventional PID controllers under identical system conditions.

Table 5. Transmission Line and STATCOM Specifications.

Parameter	Value	Unit
STATCOM Rating	5	MVA
DC-Link Capacitance	750	μF
Series Line Resistance	0.1301	Ω
Series Line Reactance	2.42	Ω
Nominal Voltage	132	Kv
Theta	180	Degree
Gain Parameters (k_P), (k_I), (k_D)	GA-Optimized	–

5.4. GA Implementation: Real-Coded vs. Binary-Coded Representation

Explicitly mention which GA encoding is used. For PID gain optimization, real-coded GA is preferred.

In this study, a real-coded Genetic Algorithm (GA) is employed for PID gain optimization. Each chromosome represents the PID gains (k_P), (k_I), (k_D) as real numbers. This approach allows smoother convergence and more precise tuning compared to binary-coded representations."

5.5. Improved GA Representation

Genetic Algorithm Flow for PID Tuning:

(1) Initialize population of chromosomes (real-coded: $[k_P$, k_I, $k_D])$
(2) Evaluate fitness function (based on performance indices: IAE, ITAE, ISE, ITSE)
(3) Selection (roulette wheel or tournament selection)
(4) Crossover (single-point or arithmetic crossover)
(5) Mutation (with defined probability)
(6) Repeat for N generations until convergence
(7) Output optimized PID gains

6. Conclusions

In this research, a three-phase Static Synchronous Compensator (STATCOM) has been created, modelled, and analyzed dynamically with a state space modelling technique, where the primary intention has been to increase the voltage stability, dynamic support, and efficiency by comparing a Regular PID controller with a Genetic Algorithm-PID (GA-PID) intelligent controller. The simulation results clearly confirm that the incorporation of the optimized control has significantly improved the voltage regulation, dynamic support, and overall reliability of the system under voltage sag conditions.

The state-space model described in this research work is a mathematical representation that captures the inherent STATCOM system dynamics, relating voltage, current, and control signals aptly. Such a model has been useful in the modelling of precise analyses that enable the forecast of performance by STATCOM under variant operational conditions. Adding a Voltage Source Converter increased the control possibilities manifold, ensuring dynamic compensation of reactive power with high speed in case of a transient event.

The comparison performed among the regular PID controller, GA-PID, and the optimized GA-PID controller showed that GA-PID performs better. With the GA-PID technique, STATCOM had a faster rise time and a shorter settling time. More importantly, it significantly reduced the percentage overshoot, which means a transient response characteristic improvement with increased damping quality of the controller. This is an indication that the controller is capable of supporting voltage stability even when a voltage sag occurs.

The reason why the GA-PID controller is so effective is the presence of the evolutionary optimizing process within the GA-PID, which enjoys the advantage of optimizing the control parameters on its own by optimizing the system's performance. Unlike the traditional PID controller, which is incapable of handling nonlinearities on its own when optimized, the GA-PID method is advantageous in adapting to the variations that exist in a modern power system characterized by intermittent power sources, high renewable energy, variable loads, and frequent power interruptions.

In addition, this research calls for the importance of intelligent optimization methods such as Genetic Algorithms in the design of control systems, since these methods will be able to provide the optimization of transient and steady-state responses, ensuring power quality and mitigating reactive power variations to provide improved voltage stability when operating on a grid.

Association of the GA-PID controls with a STATCOM system is an extremely reliable way to sort out the challenges of the power transmission system. It confirms that the inclusion of intelligent optimized controls greatly enhances the efficiency, responsiveness, and robustness of the system. The relevance of this particular research work is great in promoting the development of power system stability improvement, thereby confirming that the combined use of evolutionary algorithms with the solution of FACTS. forms a pivotal approach toward obtaining high-performance power systems.

The findings and analyses of this study considerably support the implementation of GA-PID controllers in STATCOM systems for real-time voltage regulation in modern power transmission networks. Clearly, it was demonstrated in this investigation that the GA-PID controller enhances the performance of the system by a quantum margin over and above that exhibited by the conventional PID controller, particularly in dynamic responsiveness, reduction of overshoot, settling time, and voltage stability. Various advantages of the GA-PID method make it very effective in reducing voltage sags and improving power quality, while strengthening the overall grid stability due to dynamic load variations and fault conditions. In the modern power systems that are slowly turning increasingly complex, integrating renewable energy sources, and having widely fluctuating demands, the use of adaptive and intelligent control strategies has become highly essential.

The contribution of the evolutionary optimization process in the GA-PID controller is a self-tuning mechanism, which automatically adjusts the controller parameters to ensure that optimal performance is obtained during a wide range of operating situations. Unlike the standard PID, the solution proposed by GAs gives optimal gain selection without resorting to manual tuning or heuristic methods. Thereby, it minimizes human engagement and strengthens the robustness of system nonlinearities and uncertainties. This capability is quite useful during real-time operations, where quick response and stability are at stake in order to prevent cascading failures and loss of system stability.

In light of this, it is suggested that the inclusion of GA-PID-tuned STATCOMs by power utilities and transmission system operators in present and future grid infrastructures is recommended. Besides strengthening the voltage support capability of the transmission line, these intelligent controllers damp transient oscillations, improve reactive power compensation, and enhance fault ride-through capability. This would notably enhance system resilience, reduce outages, and ensure more stable power distribution, especially in under-supplied or heavily laden transmission network areas.

In addition, future research should be directed towards hardware-in-the-loop and real-time digital simulation of the GA-PID-controlled STATCOM. This would further establish the line between theoretical modelling and actual implementation that, in fact, the proposed control scheme is able to deliver in practical scenarios. Further, hardware-in-the-loop testing will enable the researchers to study controller robustness, communication delays, and computational efficacy against realistic grid disturbances, hence giving considerable insight into large-scale commercial deployment.

The development in this regard may be done for the GA-PID framework by incorporating it with other intelligent algorithms to form hybrid methods of optimization, such as GA-PSO or GA-Fuzzy Logic controllers. Hybrid approaches can enhance convergence rate, adaptability, and precision in parameter optimization to enable the controller to cope with nonlinearities, stochastic fluctuations, and ambiguous system dynamics more precisely.

The introduction of GA-PID control in STATCOM systems, which reveals the latest approach to adaptive, effective, and intelligent voltage regulation in modern power grids. The performance of the GA-PID tuned STATCOM would contribute significantly to power system stability, dependable energy supply, and the transition toward intelligent and sustainable electrical networks through evolutionary computation and real-time optimization.

Author Contributions

O.O. carried out the research and drafted the manuscript; J.A.O. edited and finetuned the manuscript; M.O.O. supervised the research and the manuscript; D.O.A. coordinated the research and the manuscript. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement

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Data Availability Statement

This study does not involve new data.

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Conflicts of Interest

The authors declare no conflict of interest.

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