Optimal tuning of fractional-order proportional, integral, derivative and tilt-integral-derivative based power system stabilizers using Runge Kutta optimizer

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Abstract
Low-frequency power system oscillation is of great concern as it may lead to power system instability. Moreover, this action will lead to the abate capability of electric power transfer. By introducing a stabilizing signal into the excitation system, it was possible to improve the damping in the system. The power system stabilizer (PSS) provides this signal. This manuscript aims to find the optimal tuning of three different PSS controllers using a recent optimization algorithm called Runge Kutta optimizer (RUN). Based on the obtained results, the RUN shows superiority and fast convergence over competitive algorithms. In addition, the fractional-order proportional, integral, derivative (FOPID) and tilt-integral-derivative (TID) based PSS shows great damping capability over the lead–lag, PI, and FOPID-based PSS. Also, the TID-based PSS achieves better performance indices in terms of the lowest maximum overshoot and minimum settling time. Hence, it is recommended for PSS based controller.

KEYWORDS
FOPID, power system stabilizer, Runge Kutta optimization algorithm, SMIB, TID

JEL CLASSIFICATION
Electrical and electronic engineering

1 | INTRODUCTION

Fulfilling the increased consumers’ demand for electrical energy and locations of power plants that are far away from the load center needs complicated transmission and distribution network. As per its complexity, the modern electric power system stability is crucial to preserve its safe and economic operations. Small signal power system stability is one of the power system stability categories. It can be defined as the ability of the power system to recover to a normal operational condition after being subjected to a few perturbations. Moreover, it is focusing on insufficient or inadequate damping of power system oscillations. Mechanical power fluctuation as a result of loading perturbation may lead to...
low-frequency oscillations which can be in local mode or interarea oscillations. These oscillations may cause the power system generators to lose synchronism. This problem invokes the need to provide a sufficient damping torque component which can be attained by adding a power system stabilizer (PSS).

Damping devices must be properly installed in order to dampen oscillations to preserve power system stability. This can be accomplished by using flexible alternating current transmission systems (FACTS), PSS, and coordination control between them. Utilizing FACTS enables damping of low-frequency oscillations thanks to proper reactive power injection or absorption.

As per literature, recently the use of metaheuristic algorithms for the optimal tuning of lead–lag-based PSS and coordination with a different type of FACTS is noteworthy. Numerous different metaheuristic algorithms are used like, particle swarm optimization, genetic algorithms, backtracking search algorithm, Jaya algorithm, gray wolf optimizer, a hybridization of bat algorithm, gravitational search algorithm and particle swarm optimization are used in Reference 13, farmland fertility algorithm, salp swarm algorithm, kidney-inspired algorithm, whale optimization algorithm, cuckoo search, Henry gas solubility optimization, collective decision optimization algorithm, slime mold algorithm, coyote optimization algorithm.

As per the literature, no optimization algorithm can reach the global optimum for all optimization problems as per the no-free lunch theorem. In this article, a new proposed optimization algorithm called Runge Kutta optimizer (RUN) will be investigated for the robust tuning of different types of PSS. It will be used for conventional lead–lag PSS, PI, proportional, integral, derivative (PID), FOPID, and tilt-integral-derivative (TID) based PSS. Moreover, four well-known used objective functions will be utilized to illustrate the optimum PSS selected parameters.

The main contribution of this research can be summarized as follows:

1. Application for one of the latest promising optimization algorithms (RUN) in optimum tuning of power system stabilizer of SMIB.
2. Investigation of the capability of the fractional calculus-based controllers namely fractional order PID (FOPID) controller and tilt-integral-derivative (TID) for enhanced performance of PSS.
3. Inspect the use of the most common objective functions for the optimum tuning of PSS and their interaction with the investigated controllers.
4. Compare the RUN optimized parameters with previously used optimization algorithms to show the superiority of the RUN algorithm.

This article can be organized as follows, the mathematical modeling and formulation for the optimization problem will be introduced in Section 2. Section 3 will present an overview for RUN while simulation results with discussion are reported in Section 4. The main outcomes from this research will be highlighted in Section 5.

## 2  |  MATHEMATICAL MODELING AND FORMULATION

The fourth order state-space model of the synchronous generator connected to an infinite bus (SMIB) and accompanied by the conventional PSS as indicated in Figure 1 is presented in Equations (1) and (2). Also, the SMIB linearized model given by Heffron–Philips that can be used for small signal stability examination is depicted in Figure 2.

\[
\begin{bmatrix}
\Delta \delta \\
\Delta \omega \\
\Delta E'_q \\
\Delta E'_{fd} \\
\Delta V'_{o} \\
\Delta V'_{s}
\end{bmatrix} =
\begin{bmatrix}
0 & \omega_b & 0 & 0 & 0 & 0 \\
-\frac{K_1}{2H} & \frac{D}{2H} & -\frac{K_2}{2H} & 0 & 0 & 0 \\
\frac{K_4}{T_a} & 0 & -\frac{T_a}{K_5} & 1 & 0 & 0 \\
-\frac{K_4}{T_a} & 0 & -\frac{T_a}{K_6} & 1 & 0 & 0 \\
-\frac{K_{pSS}}{2H} & 0 & -\frac{T_aK_{pSS}}{2H} & 0 & -\frac{1}{T_w} & 0 \\
-\frac{T_aK_{pSS}}{2H} & 0 & -\frac{T_aK_{pSS}}{2H} & 0 & \frac{1}{T_z} & -\frac{1}{T_z} & -\frac{1}{T_z} & \frac{1}{T_z} & 0 & 0 \\
\end{bmatrix}
\begin{bmatrix}
\Delta \delta \\
\Delta \omega \\
\Delta E'_q \\
\Delta E'_{fd} \\
\Delta V'_{o} \\
\Delta V'_{s}
\end{bmatrix} +
\begin{bmatrix}
0 \\
0 \\
0 \\
0 \\
0 \\
0
\end{bmatrix}
\begin{bmatrix}
1 \\
\frac{1}{2H} \\
\frac{1}{T_a} \\
\frac{1}{T_a} \\
\frac{1}{T_w} \\
\frac{1}{T_z}
\end{bmatrix}
\begin{bmatrix}
\Delta T_m \\
\Delta V_{ref}
\end{bmatrix},
\]
The cost function of this optimization problem aims at minimizing the overshoot of the error signal, its settling time and, damping power system oscillation. The integral of absolute error (IAE), integral of time-weighted absolute error (ITAE), integral of square error (ISE), and the integral time square error (ITSE) as an indicator of performance will be utilized as an objective function to find the optimum tuning of used PSS.

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As the compensation of the phase delay between the excitation system and synchronous generator is the main function of PSS, the conventional simplified structure of lead–lag compensator is depicted in Figure 3.

The performance of PSS will be investigated in this research with the utilization of the famous fractional order calculus based controllers namely, FOPID and TID thanks to their enhanced capability of disturbance rejection and superior sensitivity to fluctuations of model parameters. The transfer function of PID, FOPID, and TID controllers can be expressed as follows:

$$\text{PID} = K_P + \frac{K_i}{s} + K_Ds,$$

$$\text{FOPID} = K_P + \frac{K_i}{s^\lambda} + K_Ds^\mu,$$

$$\text{TID} = \frac{K_i}{s^{(1/2)}} + \frac{K_i}{s} + K_Ds.$$  

3 | RUNGE KUTTA OPTIMIZER: AN OVERVIEW

Optimization algorithms aim at preserving the balance between exploration and exploitation seeking algorithm performance enhancement that solves various optimization problems. The Runge Kutta optimizer (RUN) is one of the recently proposed optimization algorithms by Iman Ahmadianfar et al. RUN employs a unique search mechanism based on the Runge Kutta technique which is one of the main parts of this algorithm. The second part is solution quality enhancement which aims at increasing the quality of obtained solutions for the investigated optimization problem besides avoiding local optima trapping. The illustration of RUN mathematical formulation will be introduced in the following subsection and supported by the flowchart in Figure 4.

3.1 | INITIALIZATION

Starting of the optimization process in RUN is accomplished by randomly initializing decision variables $x_n$ of the optimization problem by:

$$x_{n,d} = Var_{\text{min}} + \text{rand.}(Var_{\text{max}} - Var_{\text{min}}),$$

where, $Var_{\text{max}}, Var_{\text{min}}$ are a maximum and minimum range of decision variable $d$ of dimension $1,2 \ldots, D$ respectively.
3.2 | SOLUTIONS UPDATE

The well-known Runge Kutta method is used to update solutions $x_{n+1}$ at each iteration using the following equations:

\[
\text{if } \text{rand} < 0.5 \\
\quad x_{n+1} = (x_c + r.SF.g.x_c) + SF.SM + \mu.\text{randn.}(x_m - x_c) \\
\text{else} \\
\quad x_{n+1} = (x_m + r.SF.g.x_m) + SF.SM + \mu.\text{randn.}(x_{r1} - x_{r2})
\]

(11)

where, $\mu$ is a normally distributed random number and $x_{r1}, x_{r2}$ are randomly selected solutions. Also, $SF$ is an adaptive factor and $SM$ is RUN guiding search mechanism which can be calculated using Runge Kutta coefficients, $k_1 \ldots k_6$ using the following equation:

\[
SM = \frac{\Delta x}{6} x_{RK} = k_1 + 2 \times k_2 + 2 \times k_3 + k_4.
\]

(12)
3.3 | ENHANCED SOLUTION QUALITY (ESQ)

Improving solution quality, escaping from the local optima, and ensuring fast convergence are incorporated in RUN using the ESQ scheme. To employ this scheme, three new solutions will be generated namely \( x_{\text{new}1} \), \( x_{\text{new}2} \), and \( x_{\text{new}3} \) based on the following equation:

\[
x_{\text{new}1} = \beta \times x_{\text{avg}} + (1 - \beta) \times x_{\text{best}}, \quad x_{\text{avg}} = \frac{x_{r1} + x_{r2} + x_{r3}}{3}
\]

if \( \text{rand} < 0.5 \)

\[
x_{\text{new}2} = x_{\text{new}1} + r \times w \times |(x_{\text{new}1} - x_{\text{avg}}) + \text{randn}|
\]

else

\[
x_{\text{new}2} = (x_{\text{new}1} - x_{\text{avg}}) + r \times w \times |(u \times x_{\text{new}1} - x_{\text{avg}}) + \text{randn}|
\]

end

if \( \text{rand} < w \)

\[
x_{\text{new}3} = (x_{\text{new}2} - \text{rand} \times x_{\text{new}2}) + SF \times (\text{rand} \times x_{\text{RK}} + (v \times x_b - x_{\text{new}2}))
\]

end

### Table 1: Optimum parameters of investigated PSS with the corresponding objective function value

| Criteria\Param     | \( IAE \)  | \( ITAE \) | \( ISE \)  | \( ITSE \) |
|--------------------|------------|------------|------------|------------|
| \( K_{\text{PSS}} \) | 8.1884     | 14.956     | 15         | 1.2527     |
| \( T_1 \)          | 0.74052    | 0.368345   | 4.80577    | 6.7784     |
| \( T_2 \)          | 0.026641   | 0.019081   | 0.001145   | 0.030515   |
| Obj. func. value   | 3.87E-05   | 8.25E-06   | 1.75E-09   | 6.78E-10   |
| \( K_P \)          | 15         | 15         | 15         | 15         |
| \( K_I \)          | 2.13297    | 1.44756    | 15         | 15         |
| \( K_D \)          | 5.91439    | 5.23791    | 15         | 8.68461    |
| Obj. func. value   | 3.50E-05   | 8.55E-06   | 2.23E-09   | 4.46E-10   |
| \( K_P \)          | 14.7586    | 13.9354    | 15         | 14.1667    |
| \( K_I \)          | 14.9381    | 14.922     | 14.9999    | 7.41183    |
| \( K_D \)          | 6.63056    | 6.49527    | 15         | 14.4336    |
| \( \lambda \)      | 0.1        | 0.211581   | 0.1        | 0.58425    |
| \( \mu \)          | 0.964213   | 9.38E-01   | 1.00E+00   | 8.11E-01   |
| Obj. func. value   | 2.89E-05   | 8.11E-06   | 1.87E-09   | 3.59E-10   |
| \( K_P \)          | 49.9999    | 42.589     | 50         | 50         |
| \( K_I \)          | 49.9826    | 3.78423    | 50         | 50         |
| \( K_D \)          | 7.61703    | 6.49965    | 50         | 11.0807    |
| \( n \)            | 50         | 50         | 50         | 49.9998    |
| Obj. func. value   | 2.5172e-05 | 4.7802e-06 | 1.01e-09   | 2.1321e-10 |
Where, $x_b$, and $x_{best}$ are the best solution per iteration and the global best-obtained solution throughout iterations. Also, $w$ is a random number which can be calculated using iteration counter ($i$) and the maximum number of iterations ($Max_{\text{iter}}$) as in Equation (16)

$$w = rand(0, 2).\exp\left(-c\left(\frac{i}{Max_{\text{iter}}}ight)\right).$$  \hspace{1cm} (16)

**Figure 5** Change in generator angular frequency with IAE used as a cost function

**Figure 6** Change in $\Delta\omega$ with ITAE used as a cost function
Validation of the proposed use of RUN optimizer to attain the optimum parameters of lead–lag, PID, and FOPID based PSS is investigated using the Heffron–Philips model in Figure 2. The system response for a change of 0.1 p.u. in $T_m$. The parameters of the simulated model are listed in Reference 26.

The optimum parameters of investigated PSS controllers are arranged in Table 1. It is obvious from Figure 5 if the IAE performance indicator is considered, that the FOPID based PSS offers a lower maximum overshoot and reduced settling

**FIGURE 7**  Generator angular frequency response curves with ISE objective function

**FIGURE 8**  Change in $\Delta\omega$ with ITSE utilized as a cost function
time if compare with lead–lag and PI-based PSS. This can be also clarified from Figure 6 which used the ITAE as a cost function for the PSS tuning problem. The FOPID based PSS is capable of damping power oscillations faster than the lead–lag and PI PSS when the ISE cost function is utilized as shown in Figure 7. Also, the excellence of FOPID PSS is proven in Figure 8 if the ITSE is employed as an objective function.

It can be clarified clearly from Figures 5–8, that the TID-based PSS attains qualified performance indices. It reduces the maximum overshoot and settling time in comparison with PID, FOPID, and lead–lag compensators.

The superiority of the RUN optimizer in tuning FOPID and TID based PSS over the recent optimization algorithms like artificial ecosystem optimizer (AEO), gradient-based optimizer (GBO), gray wolf-cuckoo search (GWCS), and improved gray wolf optimizer (IGWO) is indicated in Figures 9 and 10 respectively. Also, Tables 2 and 3 show a comparison between investigated algorithms for tuning FOPID and TID-based PSS parameters with ITSE cost function considered which also shows the lead of the RUN optimizer.
### TABLE 2
Comparison of RUN with corresponding recent optimization algorithms for FOPID based PSS

| Optimizer\Param | RUN  | AEO  | GBO  | GWCS | IGWO  | JAYA | GWO |
|-----------------|------|------|------|------|-------|------|-----|
| $K_p$           | 15   | 14.9532 | 15   | 14.692 | 14.9871 | 1   | 50  |
| $K_i$           | 15   | 14.9177 | 15   | 14.5504 | 14.9846 | 1   | 11.5867 |
| $K_d$           | 14.3695 | 14.736 | 14.9996 | 14.2122 | 14.5472 | 14.611 | 7.09 |
| $\lambda$       | 0.1  | 0.10419 | 0.1  | 0.19202 | 0.12481 | 0.3033 | 0.85 |
| $\mu$           | 0.85931 | 0.8617 | 0.8513 | 0.86447 | 0.8479 | 0.4495 | 0.932 |
| Cost (ITSE) (*1e-10) | 3.1269 | 3.1346 | 3.1284 | 3.182 | 3.1337 | —  | —   |

### TABLE 3
Comparison of RUN with corresponding recent optimization algorithms for TID based PSS

| Optimizer\Param | RUN  | AEO  | GBO  | GWCS | IGWO |
|-----------------|------|------|------|------|------|
| $K_t$           | 50   | 49.9689 | 50   | 50   | 49.9965 |
| $K_i$           | 50   | 49.9331 | 50   | 20.0894 | 49.5237 | 49.9995 |
| $K_d$           | 11.0808 | 11.1029 | 10.8215 | 11.2048 | 10.9484 |
| $n$             | 49.9998 | 49.8542 | 49.0968 | 38.4335 | 49.9081 |
| Cost (ITSE) (*1e-10) | 2.1321 | 2.1333 | 2.3234 | 2.1395 | 2.1324 |

## 5 Conclusion

The optimum tuning of different PSS parameters using RUN as one of the recently introduced optimization algorithms is investigated in this research manuscript. Various cost functions are utilized to explore the capability of RUN to get the optimum parameters with minimum overshooting and settling time considered. It was shown that the use of FOPID and TID-based PSS are capable of damping low-frequency oscillation in comparison with conventional lead-lag and PID-based PSS. The TID-based PSS achieves better performance indices in terms of the lowest maximum overshoot and minimum settling time. Hence, it is a better choice for PSS controllers if compared with FOPID, PID, and conventional lead–lag compensator. The performance of TID-based PSS in a multimachine power system will be investigated in the upcoming research work.

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Research data are not shared.

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The authors declare no potential conflict of interest.

### Author Contributions
Mahmoud Abbas El-Dabah: Conceptualization (equal); data curation (equal); formal analysis (equal); investigation (equal); methodology (equal); resources (equal); software (equal); validation (equal); visualization (equal); writing – original draft (equal). Salah Kamel: Resources (equal); software (equal); supervision (equal); validation (equal); visualization (equal); writing – original draft (equal); writing – review and editing (equal). Mohammed A Abido: Resources (equal); software (equal); supervision (equal); validation (equal); visualization (equal); writing – review and
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