

A Meta-Heuristic based Solution for Mitigating Sub-Synchronous Resonance in Grid-connected Wind Farms

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ABSTRACT

This study proposes a novel optimization strategy for tuning the parameters of a Rotor Side Converter (RSC), employing a hybrid approach that integrates three advanced optimization algorithms: Particle Swarm Optimization (PSO), Cuckoo Search Algorithm (CSA), and Grey Wolf Optimizer (GWO). The proposed method is integrated with existing damping techniques on both the grid side, using a Thyristor Controlled Series Capacitor (TCSC) and the wind farm side, utilizing a Supplementary Damping Controller (SDC) to enhance the Sub-Synchronous Oscillation (SSO) damping effectiveness. Based on the IEEE First Benchmark and the IEEE 14-bus system, time-domain simulations and small-signal stability analysis demonstrate that the proposed solution significantly improves the damping performance under critical operating conditions, particularly high series compensation levels and low wind speeds. The MATLAB/Simulink tool was also employed in this study.

Keywords-Sub-Synchronous Resonance (SSR); thyristor-controlled series capacitor (TCSC); meta-heuristic algorithms; DFIG-based wind farm; supplementary damping controller (SDC)

I. INTRODUCTION

The high penetration of wind farms has introduced new stability challenges, classified as Sub-Synchronous Resonance

(SSR) stability [1]. The terms SSO and SSR are used interchangeably throughout this paper. In SSR classification, the Induction Generator Effect (IGE) and Sub-Synchronous Control Interaction (SSCI) are considered purely electrical

resonance phenomena. IGE occurs due to the interaction between the turbine-generator system and the series-compensated transmission line, whereas SSCI is a newly emerging instability phenomenon, caused by the involvement of power electronic interfaces in wind turbine generators. In the past, SSO was first observed in 1970 at the Mohave Power Station due to the interaction between a turbine-generator and a 500 kV series-compensated transmission line [2]. In 2009, the first SSCI-related incident was detected by the Electric Reliability Council of Texas (ERCOT), with the identified cause being the interaction between the Doubly-Fed Induction Generator (DFIG) control system and the series-compensated transmission line [3]. Recently, Multi-Terminal DC (MTDC) grids have also been identified as contributing factors to SSO when integrated with wind farms, where MTDC acts as a virtual capacitor interacting with the DFIG [4]. These studies indicate that SSO poses a significant threat to the stability of both current and future power systems.

Authors in [5] provide an overview and categorization of SSO mitigation solutions into two main approaches: grid side and wind farm side solutions. On the grid side, Flexible AC transmission Systems (FACTS) play a crucial role in enhancing system stability by providing reactive power support, improving voltage profiles, and managing power flows, thereby effectively addressing the challenges posed by IGE in power systems [6]. Regarding wind farm-side solutions, modifying the control loops and optimizing the control parameters of the DFIG are two primary approaches to mitigate the SSCI. Tuning the control loops of a RSC and a Grid Side Converter (GSC) using supplementary controllers has been widely applied in SSO research. Authors in [7] adjusted the RSC control loop by integrating resonant controllers. Time-domain simulations and eigenvalue analyses based on the IEEE First Benchmark model demonstrated the robust SSO damping capability of the proposed controller. Similarly, authors in [8] introduced an adaptive control strategy consisting of two key components: a Sub-Synchronous Frequency Estimator (SSFE) and an Adaptive Sub-Synchronous Damping Controller (ASDC). The SSFE detects SSO modes and accurately tracks their sub-synchronous frequencies, while the ASDC extracts SSO signals using voltage measurements, generates appropriate current signals, and injects them into the grid. Besides tuning the DFIG control loops, many studies have also adopted an alternative approach based on control parameter optimization to enhance positive damping in DFIG-based wind power systems. The PI parameters of the RSC and GSC were optimized by integrating the Non-Dominated Sorting Genetic Algorithm III (NSGA-III) with a dimensionality reduction process using t-distributed Stochastic Neighbor Embedding (t-SNE) [9]. The simulation and experimental results demonstrated the effectiveness of this approach in mitigating SSR and SSCI. However, the parameter optimization process is complex and challenging to implement, owing to the multiple procedural steps involved. Authors in [10] applied an improved PSO algorithm to optimize the parameters of the SDC, which was integrated into the RSC control loops. Although the optimized SDC parameters significantly improved SSR damping under various operating conditions, the algorithm required numerous iterations to find

the optimal solution. Moreover, the stability performance of these optimized parameters has not been evaluated.

The present study proposes a combined approach that integrates parameter optimization using meta-heuristic algorithms with existing grid side and wind farm side solutions, as illustrated in Figure 1. The main contributions of this paper include:

- Proposing an optimization approach using PSO, CSA, and GWO algorithms to fine-tune the RSC control parameters.
- Integrating the optimized parameters with a grid side solution utilizing TCSC, and a wind farm side solution using SDC to alleviate SSR.

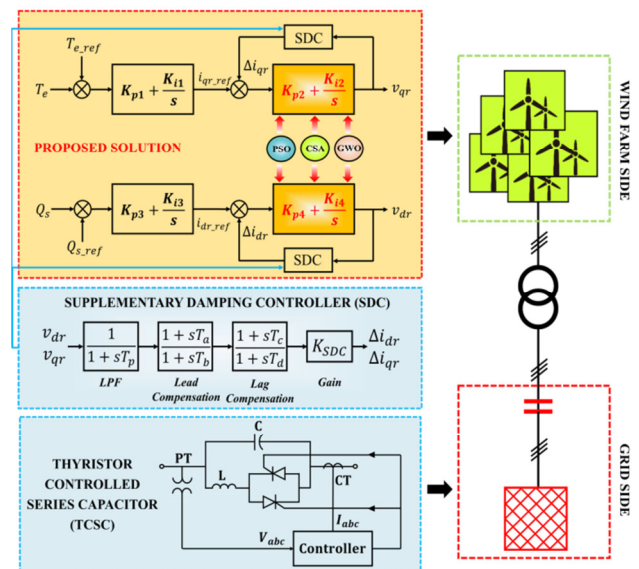


Fig. 1. The SSO damping enhancement strategy based on meta-heuristic optimization.

II. TESTED SYSTEM

Figure 2 provides a detailed view of the wind farm based on the IEEE First Benchmark, which is connected to the grid via a 161 kV series-compensated transmission line. This system has been widely accepted in numerous SSR analysis studies [6, 7, 11, 12]. This wind farm model is represented in the form of state matrices based on MATLAB to facilitate the small-signal analysis of the system [11]. The IEEE 14-bus model was used to simulate the power grid connected to the wind farm [13]. Finally, the tested system was modified by replacing the generator at bus 2 of the IEEE 14-bus model with a DFIG-based wind farm.

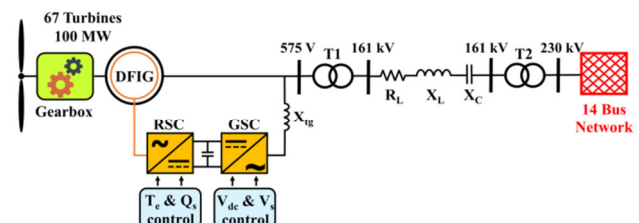


Fig. 2. The wind farm system based on IEEE first benchmark.

III. PROPOSED SOLUTION

The proposed optimization solution significantly reduces the computational burden by focusing on two key parameters of the RSC ($K_{p2} = K_{p4}$, $K_{i2} = K_{i4}$). The process of tuning the parameters includes four steps. First, the range of parameters was set as follows: $0 \leq K_{p2}, K_{p4} \leq 0.1$ and $0 \leq K_{i2}, K_{i4} \leq 1$. Next, the simulation model was launched using the command sim("Simulink project"). During the simulation runtime, the PSO, CSA, and GWO algorithms were comparatively applied for the continuous updating of optimal solutions [14-16]. The parameters were optimized by minimizing the objective function defined in (1) [17]. Finally, the optimal parameters were applied for the validation process.

$$\Delta P = P_{ref} - P_e \quad (1)$$

where P_{ref} is the reference output power and P_e is the actual output power corresponding to the wind speed [11].

The Integral of Time-Weighted Absolute Error (ITAE), as estimated from (2), was used to determine the stopping condition of the algorithms. The best algorithm was determined based on the smallest average number of iterations and the ITAE value. Additionally, the parameters obtained from the algorithm that yielded the lowest ITAE were selected.

$$ITAE = \int_0^t t|e(t)|dt \quad (2)$$

where $e(t)$ is the error of power and t is the simulation time.

Factors, such as the wind speed, compensation level, or system impedance, were considered as inputs to the proposed solution. Meta-heuristic algorithms continuously search for optimal parameters in response to varying input conditions, aiming to satisfy the predefined ITAE value of the objective function.

The iteration count and ITAE were employed as key performance indicators. The former quantifies the convergence speed of the optimization algorithm, where fewer iterations imply a faster system adaptability to SSR. The latter evaluates the damping performance under varying operating conditions, with lower ITAE values indicating an improved response accuracy and system stability. From Table I, it is evident that CSA demonstrates superior performance in continuous parameter optimization owing to its efficient global search capability enabled by Lévy flights. As a result, CSA achieves the optimal parameters more quickly (with the lowest number of iterations, only 1.4) while still ensuring system stability (with the smallest ITAE of 22446.22). The optimized parameters obtained from PSO and GWO also contribute to system stability; however, these algorithms require more iterations due to their optimization mechanisms, which are more susceptible to being trapped in local extrema.

Unlike trial-and-error tuning methods or traditional gradient-based approaches, these meta-heuristic algorithms offer the advantage of ease of tuning and strong adaptability to nonlinear systems, such as the wind power control system. Moreover, the intelligent algorithm-based solution significantly reduces hardware investment costs compared to the deployment of FACTS devices

IV. RESULTS AND DISCUSSION

The proposed solution was sequentially combined with the existing solutions on each side when connecting the wind power system to a series-compensated transmission line at $t = 15$ s. Critical operating scenarios with K_C ranging from 60% to 75%, and V_w ranging from 6 m/s to 7 m/s were applied to validate the proposed solution. Additionally, an eigenvalue analysis was conducted to further demonstrate the significant improvement in SSO damping. Specifically, eigenvalues ($\lambda = \sigma \pm \omega i$) with negative real parts indicate that the system is stable because they correspond to a positive damping ratio ($\zeta = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}}$) and vice versa.

A. FACTS-based Solution Improvement

The TCSC was applied as an existing solution on the grid side based on a constant power control strategy, as stated in [18]. Before combining the optimized RSC parameters, the TCSC could not return the system to a stable state with the occurrence of SSO, as shown in Figures 3 and 4, except for the case when $V_w = 7$ m/s and $K_C = 60\%$.

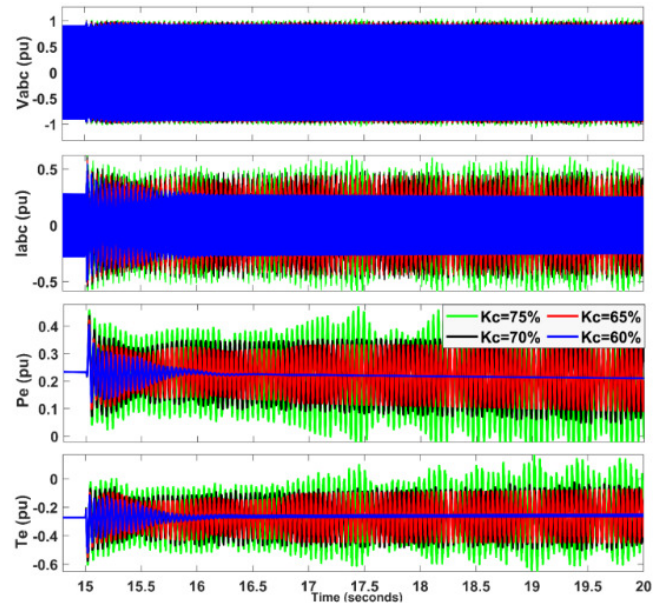


Fig. 3. SSR damping effectiveness of the TCSC at $V_w = 7$ m/s and high compensation levels.

The damping effectiveness improved significantly when the optimized RSC parameters were combined with the TCSC, because the system maintained stability across all test scenarios, as displayed in Figures 5 and 6. Furthermore, the system takes only about 0.3 sec to restore stability, with all monitored signals. The eigenvalue analysis, in Table II, also aligns with the simulation results, indicating that the combination of the proposed method with TCSC consistently achieves a positive damping ratio in all examined cases.

TABLE I. OPTIMAL RESULTS OBTAINED FROM PSO, CSA, AND GWO

No	PSO				CSA				GWO			
	K_p_{PSO}	K_i_{PSO}	Iter	ITAE	K_p_{CSA}	K_i_{CSA}	Iter	ITAE	K_p_{GWO}	K_i_{GWO}	Iter	ITAE
1	0.0199	0.0354	8	20381.78	0.0056	0.1457	1	21565.19	0.0220	0.1753	1	22745.60
2	0.0054	0.2973	5	21777.62	0.0244	0.0983	1	22828.93	0.0080	0.3857	4	20667.06
3	0.0193	0.5230	2	23261.09	0.0204	0.3245	2	22796.40	0.0236	0.2673	1	23766.61
4	0.0170	0.6660	2	24270.53	0.0097	0.3463	1	20883.29	0.0139	0.2659	3	21363.01
5	0.0224	0.0182	4	24584.80	0.0012	0.1314	2	22215.63	0.0100	0.7426	4	23601.94
6	0.0010	0.3433	3	21947.14	0.0073	0.1838	1	21746.19	0.0260	0.2498	1	24687.45
7	0.0042	0.4706	7	20660.72	0.0063	0.6898	3	22840.67	0.0175	0.2460	9	21913.17
8	0.0202	0.5201	5	23562.56	0.0032	0.8672	1	24247.03	0.0082	0.2093	6	21645.31
9	0.0061	0.5910	4	21699.51	0.0170	0.2265	1	21713.29	0.0135	0.5923	2	22429.41
10	0.0198	0.2411	1	22435.49	0.0205	0.5148	1	23625.54	0.0183	0.6488	4	24468.47
Average			4.1	22458.12			1.4	22446.22			3.5	22728.8

TABLE II. SSR ANALYSIS RESULTS FOR THE TCSC-BASED SOLUTION IMPROVEMENT

Wind speeds (V_w)	Compensation levels (K_C)	TCSC		TCSC + Optimal parameters	
		Eigenvalue (λ)	Damping ratio (ζ)	Eigenvalue (λ)	Damping ratio (ζ)
7 m/s	60%	$-0.3 \pm 175.8i$	0.0017	$-7.8 \pm 170.2i$	0.0458
	65%	$0.5 \pm 168.5i$	-0.0036	$-7.4 \pm 161.7i$	0.0457
	70%	$1.2 \pm 161.8i$	-0.0074	$-6.8 \pm 153.7i$	0.0442
	75%	$1.9 \pm 155.7i$	0.0122	$-6.1 \pm 146.3i$	0.0417
6 m/s	60%	$2.4 \pm 179.4i$	-0.0134	$-5.4 \pm 171.5i$	0.0315
	65%	$3.2 \pm 172.9i$	-0.0185	$-4.5 \pm 163.6i$	0.0275
	70%	$3.9 \pm 167.1i$	-0.0233	$-3.4 \pm 156.4i$	0.0217
	75%	$4.5 \pm 162.0i$	-0.0278	$-2.2 \pm 149.9i$	0.0147

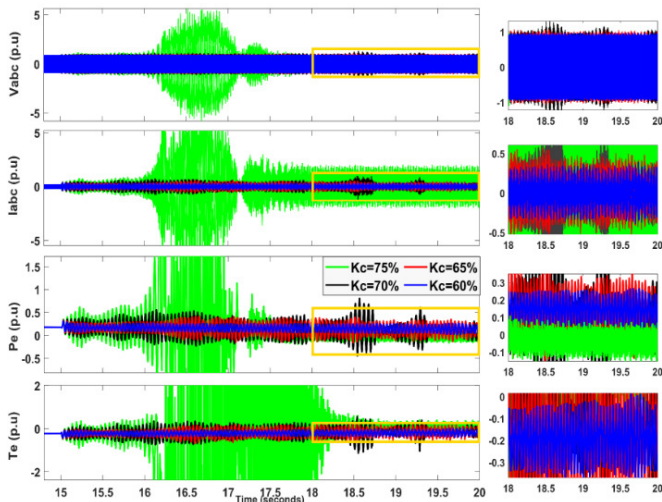


Fig. 4. SSR damping effectiveness of the TCSC at $V_w = 6$ m/s and high compensation levels.

B. Supplementary Damping Controller –based Solution Improvement

This study applies the RSC control loop modification by adding SDC. This solution is considered an existing method on the wind farm side based on the DFIG, as discussed in [17]. Initially, only the SDC solution was implemented in the critical operating scenarios. Figures 7 and 8 demonstrate that the system only maintains stability at a wind speed of 7 m/s and a compensation level from 60% to 65%, but experiences severe instability under the remaining operating conditions. Subsequently, when combined with the optimized RSC parameters, obtained from the CSA, the SSO oscillations were

quickly and effectively damped in all cases. Specifically, Figures 9 and 10 demonstrate that the monitored signals returned to the permissible threshold within approximately 0.5 s. Moreover, the damping effectiveness of the SSO, provided by the optimized RSC parameters, was significantly improved, with the real parts of the eigenvalues being negative, as presented in Table III.

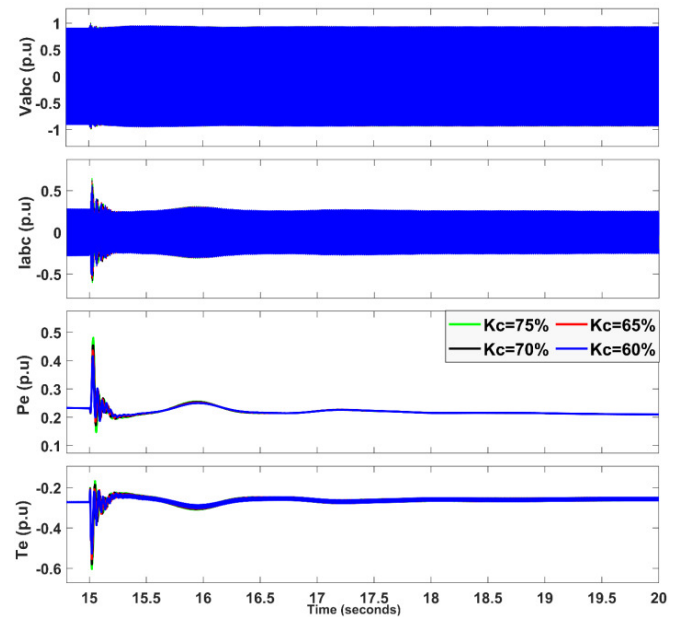


Fig. 5. SSR damping effectiveness of the TCSC combined with optimal RSC parameters at $V_w = 7$ m/s and high compensation levels.

TABLE III. SSR ANALYSIS RESULTS FOR THE SDC-BASED SOLUTION IMPROVEMENT

Wind speeds (V_w)	Compensation levels (K_C)	SDC		SDC + Optimal parameters	
		Eigenvalue (λ)	Damping ratio (ζ)	Eigenvalue (λ)	Damping ratio (ζ)
7 m/s	60%	$-1.0 \pm 172.3i$	0.0058	$-7.7 \pm 165.6i$	0.0464
	65%	$-0.4 \pm 165.2i$	0.0024	$-7.2 \pm 157.4i$	0.0457
	70%	$0.1 \pm 158.7i$	-0.0006	$-6.6 \pm 149.7i$	0.0440
	75%	$0.6 \pm 152.8i$	-0.0039	$-5.8 \pm 142.5i$	0.0407
6 m/s	60%	$1.5 \pm 176.1i$	-0.0098	$-5.0 \pm 167.2i$	0.0299
	65%	$2.1 \pm 169.9i$	-0.0123	$-4.0 \pm 159.6i$	0.0251
	70%	$2.7 \pm 164.3i$	-0.0164	$-2.9 \pm 152.8i$	0.0190
	75%	$3.0 \pm 159.3i$	-0.0188	$-2.0 \pm 146.8i$	0.0136

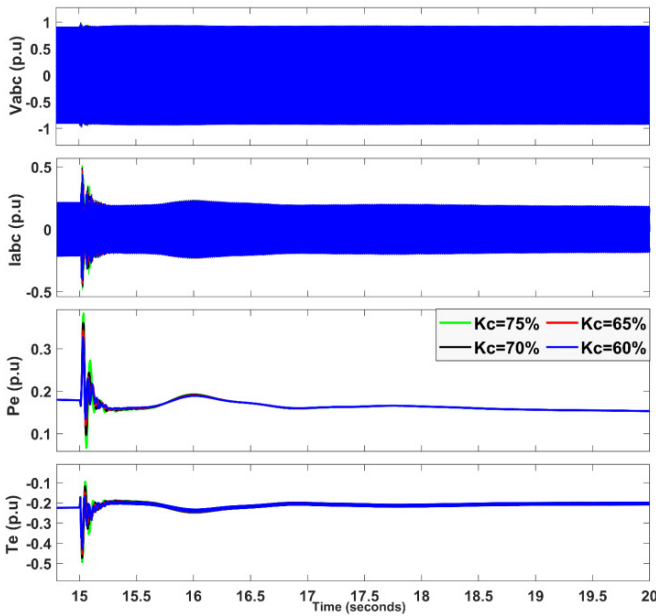


Fig. 6. SSR damping effectiveness of the TCSC combined with optimal RSC parameters at $V_w = 6$ m/s and high compensation levels.

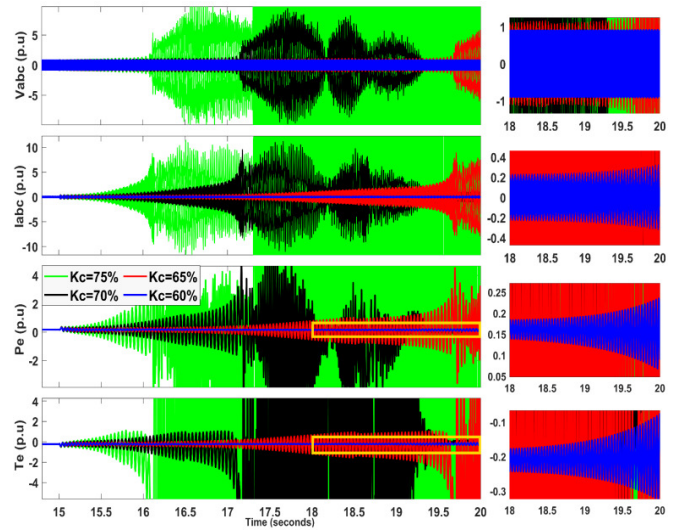


Fig. 8. SSR damping effectiveness of the SDC at $V_w = 6$ m/s and high compensation levels.

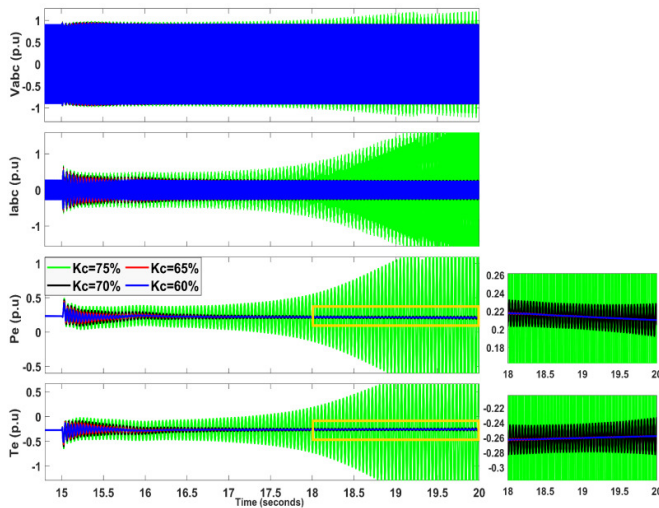


Fig. 7. SSR damping effectiveness of the SDC at $V_w = 7$ m/s and high compensation levels.

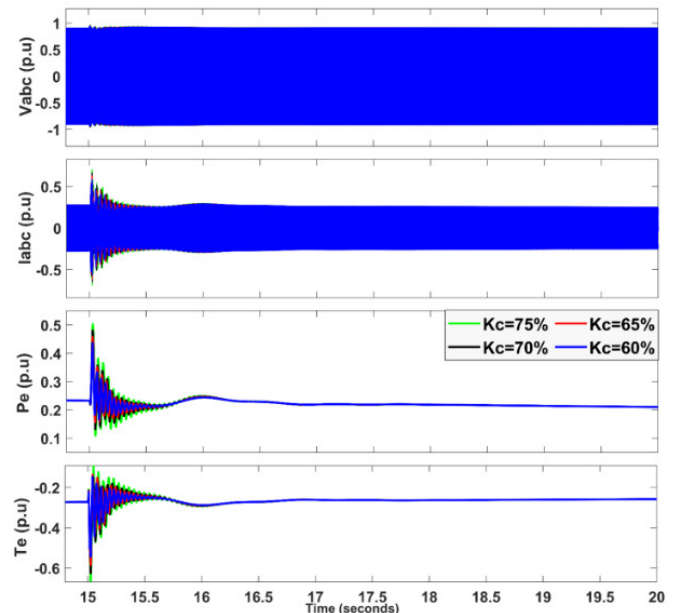


Fig. 9. SSR damping effectiveness of the SDC combined with optimal RSC parameters at $V_w = 7$ m/s and high compensation levels.

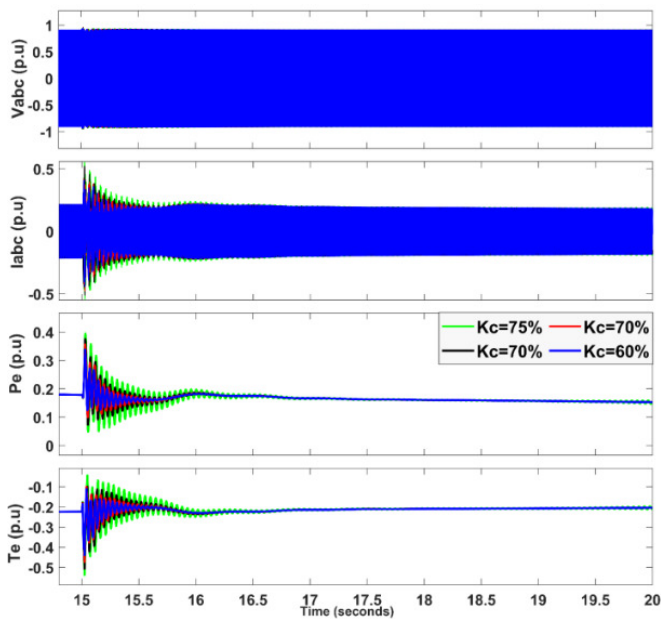


Fig. 10. SSR damping effectiveness of the SDC combined with optimal RSC parameters at $V_w = 6$ m/s and high compensation levels.

V. CONCLUSIONS

This study proposes the application of meta-heuristic algorithms, including Particle Swarm Optimization (PSO), Cuckoo Search Algorithm (CSA), and Grey Wolf Optimizer (GWO), to optimize the control parameters of the current controller within the Rotor Side Converter (RSC). Among them, the CSA algorithm demonstrated superior performance by achieving optimal results quickly (with 1.4 iterations) and good control quality (Integral of Time-weighted Absolute Error (ITAE) of 22446.22). Through time-domain simulation results and eigenvalue analysis, it was proven that the optimal parameters obtained from the CSA effectively improved Sub-Synchronous Oscillation (SSO) damping when combined with the grid-side solution based on the Thyristor Controlled Series Capacitor (TCSC) and the wind farm-side solution using the Supplementary Damping Controller (SDC). In future work, the research will be extended to incorporate real-time testing using RTDS or OPAL-RT under various conditions. An evaluation of the economic aspects of implementing the proposed solution in practice will also be considered.

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