



Optimal Sizing of Supercapacitor Energy Storage Based on Firefly Algorithm for Enhancing Critical Clearing Time

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Abstract: In the present day, the electrical power demand is increasing and expected to continue growing. The renewable energy sources as the power supply are also increasing but not much as needed. As a result, the power systems operate close to their maximum stability limit. This paper proposed to extend the value of Critical Clearing Time (CCT) to enhance the stability system, especially the transient stability. A Supercapacitor Energy Storage (SCES) is installed at one of the generator bus; however, the sizing of SCES must be optimized due to the economics and power balance constraint. In this paper, the Firefly Algorithm (FA) is used to obtain the optimal sizing of SCES with the objective function is the highest value of CCT. Lagrange interpolation is used to validate the effectiveness of FA, such as computation time and accuracy. According to the simulation result obtained, the proposed method using FA has a faster calculation time than Lagrange interpolation. Moreover, the proposed method is validated on a modified IEEE 9 bus with various cases. By using FA, the best increase of CCT is obtained when the optimal size of SCES is 0.120 p.u. The overall CCT increase is 0.15766s or around 54.61%.

Keywords: Critical clearing time, Firefly algorithm, Supercapacitor energy storage, Transient stability.

1. Introduction

In recent years, a promising and critical intelligent generation known as the smart grid becomes the main issue in the power system. The incremental supply for electrical energy is needed due to the escalation of the industry and modern technologies. The power systems are forced to operate near their stability limits due to very complex and nonlinear conditions. Many countries use the Renewable Energy Source (RES) to increase the supply energy with less carbon [1]. However, the interconnection system between RES and the main grid must be resilient and efficient. The next challenge is the instabilities and the security of the power system in synchronizing RES and the main grid [2–4]. Moreover, the power system's continuity and reliability when any disturbance happened in the system must be maintained. The protection system

must secure the system and ensure the stability of the power system. Thus, the monitoring study of transient disturbance is needed to know the effects on system protection [5, 6].

Several types of research related to power system stability, such as the fastest identification, detection, and managing the power system, are needed to improve the online monitoring assessment in the power system. Machine learning approaches are used to learn the stability and the security of the power system [2]. In enhancing the power quality, swarm intelligence, such as the firefly algorithm, particle swarm, ant bee colony, and others, are used to enhance the power quality [7].

Rani and Ramakrishnan use modified particle swarm optimization, such as the binary particle swarm optimization and unified particle swarm optimization. The radial power distribution system is chosen to be the test system to get the optimal

network reconfiguration with the addition of a distributed generator [8, 9]. The enhance water cycle algorithm and grey wolf's algorithm are proposed by [10, 11] for power system distribution. [10, 11] focuses on enhancing the voltage stability index and minimizing the system power losses. However, some papers mention that the firefly algorithm is better than genetic algorithms, particle swarm optimization, and artificial bee colonies because they can be implemented in parallel. Moreover, the firefly algorithm is more efficient in finding global optima with a higher success rate [12, 13].

The firefly algorithm was proposed by Balachennaiah to optimize the real power loss and voltage stability index for a large transmission network. Balachennaiah validated that the firefly algorithm has a better result than a real coded genetic algorithm and interior-point successive linear programming technique [14]. Jagatheesan proposed the design of a proportional-integral-derivative controller for an automatic generation control for a multi-area power system. Firefly algorithm shows a better result compared with other optimization algorithms, such as genetic algorithm and particle swarm optimization technique [15]. Moreover, a chaotic firefly algorithm and adaptive modified firefly algorithm were used to optimize the overcurrent relay coordination [16–18]. To enhance the power system stabilizer controller, a firefly algorithm was proposed in each machine for tuning the controller [19, 20]. A self-adaptive firefly algorithm to obtain the optimal placement of flexible alternating current transmission systems is proposed by [21]. Moreover, the firefly algorithm was proposed by [22] in optimizing the controller of generation control in a system with a unified power flow controller and Superconducting Magnetic Energy Storage (SMES).

SMES and Supercapacitor Energy Storage (SCES) are examples of the energy storage system that can improve the power system stability, especially transient stability. It acts as an additional damping that reduces the oscillation when a large disturbance happens. Liu proposed the "plug and play" rules to optimize the SMES operation in the smart grid [23]. The reinforcement learning method proposed by [24] for SMES device to increase the transient stability. On the other hand, SCES was proposed to extend the critical clearing time value when a large disturbance occurs in the system. As a result, the system has additional time to avoid the worst condition [25, 26]. [27] shows that the differential evolution algorithm can be used to optimize the generator's critical clearing time. However, it only validated in a single machine to an

infinite bus and calculated the critical clearing time using equal area criterion. However, the latest research shows that SCES has more advantages than SMES, such as higher power density, has fast charging and discharging, high reliability, durability, maintenance-free, and environment save [28, 29].

In this paper, it is motivated to perform the SCES sizing optimization with the objective of enhancing the transient stability using FA. FA is chosen because it has faster calculation than others standard interpolation calculation. In this paper, Lagrange interpolation is used for the comparison with the proposed method. The objective function of both method is obtaining the highest CCT value. In addition, different cases for the fault location are presented to verify and highlight the effectiveness of the proposed method. A modified IEEE 3-machines 9-bus system was chosen to carry out the different cases.

Accordingly, the remainder of the paper is organized as follows. Section 2 present the notation list of the variables that used in this paper. A brief description of transient stability assessment is articulated in Section 3. Section 4 describes the proposed method in finding the sizing of the SCES. The result and discussion of the proposed method is demonstrated in Section 5. Finally, Section 6 concludes the research works and the future works.

2. Nomenclature and abbreviations

The following notations will be used in this paper.

M_i	inertia constant of generator i
M_T	total of inertia constant
ω_0	initial synchronous speed
ω_i	synchronous speed of generator i
$\tilde{\omega}_i$	$\omega_i - \omega_0$
P_{mi}	mechanical power of generator i
P_{ei}	electrical power of generator i
P_{SCES}	SCES power
$P_{SCES,min}$	minimum value of SCES power
$P_{SCES,max}$	maximum value of SCES power
P_{COA}	center of angle/inertia power
D	damping
δ_0	initial rotor position
δ_i	rotor position of generator i
θ_i	$\delta_i - \delta_0$
Y_{ij}	admittance matrix
E_{ij}	internal voltage of the generator
I	light intensity variation of firefly
I_0	original light intensity of firefly
α	randomization parameter determined based on the complexity of the problem, which is from the interval [0,1]

β	the attractiveness of firefly
β_0	initial attractiveness of firefly at $r = 0$
γ	absorption coefficient which controls the decrease of the light intensity
$r_{i,j}$	distance between two fireflies i and j at x_i and x_j
$x_{i,k}$	k th component of the spatial coordinate x_i of the i th firefly
d	dimension number of the problem
ε_i	vector of random numbers chosen from uniform distribution or Gaussian distribution

Abbreviation

RES	renewable energy source
SCES	supercapacitor energy storage
SMES	superconducting magnetic energy storage
CCT	critical clearing time
FA	firefly algorithm
UEP	unstable equilibrium point

3. Power system stability assessment

Transient stability known as the large-disturbance rotor angle stability, is the ability of the synchronous machines which are interconnected to maintain its synchronism after a large disturbance happens [30]. The equilibrium of the electromagnetic torque and mechanical torque is essential in determining the stability of the system. The angular swing is increasing due to the instability and lead to losing synchronism of the generators. Transient instability is the main cause of the power instability problem, including islanding and blackout in some countries.

The transient stability index is measured through Critical Clearing Time (CCT), which is defined as the fault clearing time when the system becomes stable after the fault clearance. If the fault clearing time exceeds the CCT, the system becomes unstable; otherwise, it is stable. There are two main methods in calculating CCT, such as direct method and indirect method. An indirect method, known as the conventional numerical method or time-domain simulation method, is believed to have good accuracy. The drawback of the indirect method is providing a range of approximated CCT, but the specific value can be found by adjusting the fault duration time through trial and error [31, 32]. The direct method uses various numerical integration to obtain the CCT value, such as equal area criterion, energy-function method, critical trajectory method, and others. Equal area criterion and energy-function method use energy balance to obtain the CCT value [33].

In this paper, the CCT is obtained using the critical trajectory method. The critical trajectory method used four trajectories to imply the method: the on-fault trajectory, the stable trajectory, the unstable trajectory, and the critical trajectory. The critical trajectory is the trajectory, which is located between stable and unstable trajectory [34, 35]. The endpoint condition of the critical trajectory is the Unstable Equilibrium Point (UEP), where each machine has its UEP value.

Some researchers proposed various alternatives in enhancing the power system stability, especially transient stability. One of the alternatives methods is by extending the CCT. By extending the CCT value, the protection system has more time to respond when a disturbance happens. It becomes an alternative when the protection system has mal-tripping due to false sensing or error in the protection system. With the increase of the CCT, the delay can be tolerated for a fraction of a second. As a result, the system operators able to evaluate and organize the corrective action to preserve the power system stability to avoid the failure and blackout [36].

Supercapacitor Energy Storage (SCES) has a high response time and ramp rate capability, which is in accordance with the needs of transient stability. The SCES works to damp the oscillation in transient time because the governor system cannot absorb the frequency fluctuation due to the governor is a slow response device. Recent researches show that SCES has more advantages than other energy storage devices. SCES has an extremely high power density and fast charging/discharging rather than other energy storage devices. SCES is adequate for the application in the remote sites because it has a longer lifetime and maintenance-free. SCES is also known as environmentally friendly because it is easily recycled. Moreover, the efficiency of SCES is around 75-95% [28, 29].

Firefly Algorithm (FA) is one of the nature-inspired algorithms, a meta-heuristic optimization algorithm that depicts the characteristics of fireflies developed by Xin She Yang [37]. There are three idealized behavior rules in FA: The first rule is that all the fireflies are unisexual, and sex has no effect on their movement. It moves toward the brightness ones. The second rule is that the degree of attractiveness is proportional with their brightness. The one with less bright will move towards to the brighter one. If there the fireflies have the same brightness, it will move randomly. The final rule is the value of the objective function to be optimized becomes the brightness firefly.

The advantage of the FA is the ability that divides the initial population into a subgroup. FA has been

proven to be efficient at solving the optimization problems than other meta-heuristic algorithms related to nonlinear optimization problems, which is suitable for the transient stability assessment. Moreover, some researches proved that FA gives an excellent result more than other algorithms. In this paper, FA is used as the option to do the online monitoring in stability assessment. Using FA, the calculation is faster than the previous method, such as calculating using Lagrange interpolation method and manually.

4. Problem formulation

4.1 Power system modelling

In this paper, a modified IEEE 3-machine 9-bus used to validate the proposed method. The modified system consists of one main grid and two small renewable energies, as depicted in Fig. 1. The system is assumed to have a double circuit line transmission. To enhance the transient stability, the SCES is installed at bus generator 2. A three-phase fault is subjected to the system to check the CCT value of the system.

There are several points of fault to test the proposed method, which explained as follows:

- Fault point A located between bus 2 and 7, but it near to bus 2
- Fault point B located between bus 3 and 9, but it near to bus 3
- Fault point C located between bus 4 and 5, but it near to bus 4
- Fault point D located between bus 4 and 6, but it near to bus 4
- Fault point E located between bus 5 and 7, but it near to bus 7
- Fault point F located between bus 7 and 8, but it near to bus 7
- Fault point G located between bus 6 and 9, but it near to bus 9
- Fault point H located between bus 8 and 9, but it near to bus 9
- Fault point I located between bus 8 and 9, but it near to bus 8

The swing equation model of the power system is described as follows:

$$M_i \ddot{\omega}_i = P_{mi} - P_{ei}(\theta) - \frac{M_i}{M_T} P_{COA} - D_i (\tilde{\omega}) - P_{SCES} \quad (1)$$

$$\dot{\theta}_i = \tilde{\omega}_i \quad (2)$$

where:

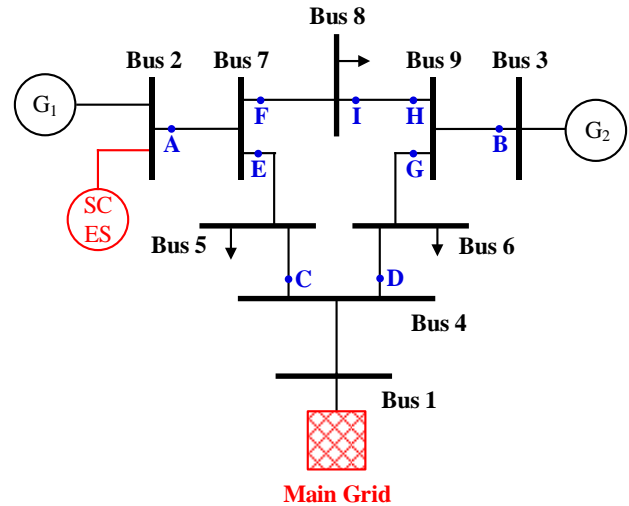


Figure. 1 Single line diagram of modified IEEE 3-machine 9-bus system

$$M_T = \sum_{i=1}^n (M_T) \quad (3)$$

$$P_{ei}(\theta) = \sum_{j=1}^n (Y_{ij} E_i E_j \sin (\theta_i - \theta_j + \alpha_{ij})) \quad (4)$$

$$\theta_i = \delta_i - \delta_0 ; \tilde{\omega}_i = \omega_i - \omega_0 \quad (5)$$

$$P_{COA} = \sum_{i=1}^n (P_{mi} - P_{ei}(\delta)) \quad (6)$$

M is the inertia constant, ω is the synchronous speed, P_{ei} is the electrical power, P_m is the mechanical power, P_{SCES} is the SCES power, D is the damping, and δ is the rotor position. Moreover, Y_{ij} , E_{ij} , and α_{ij} are the admittance matrix, an internal voltage of the generator, and constants, respectively.

4.2 Modified lagrange interpolation

Modified Lagrange interpolation is a polynomial interpolation to get the certain values at the arbitrary points. It can be used to get the value of SCES by calculating the CCT at first. The first derivative of the function is used to get the optimal value of SCES. However, the result must be validated using others method or using a ranking method. As a result, this method is time consuming compared with the meta-heuristic method. Thus, this method cannot be used for stability online monitoring assessment. The pseudocode of Lagrange interpolation is shown below.

Algorithm for Modified Lagrange Interpolation.

```

Start

% Calculating CCT using critical trajectory
method
    
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% Sizing SCES
Read number of data (k)
Read data :
  For i = 1 to k
    Read  $x_i$  and  $y_i$ 
  Next i
Read  $x_p$ 
Initialize P = 0
For i = 1 to k
  L(i) = 1
  For j = 1 to k
    If  $i \neq j$ 
      L(i) = L(i) * (( $x_p - x_j$ ) / ( $x_i - x_j$ ))
    End if
  Next j
  P = P + L(i) *  $y_i$ 
Next i
Print P

% Defining the optimal SCES value
If  $CCT_n > CCT_{n+1}$ 
  Then  $CCT_{new} = CCT_n$ 
  Else  $CCT_{new} = 0$ 
If  $CCT_{new} = CCT_n$ 
  If  $P_{SCES\ n} < P_{SCES\ n+1}$ 
    Then  $P_{SCES\ new} = P_{SCES\ n}$ 
  Else 0
Else 0

End

```

4.3 Firefly algorithm

For the proper design of FA, the variation of light intensity, I , and the attractiveness, β , is needed. The light intensity varies with the distance, r , is given as follows:

$$I = I_0 \exp(-\gamma r^2), \quad (7)$$

where I_0 , r , and γ are the original light intensity, the distance between fireflies, and the absorption coefficient, which controls the decrease of the light intensity, respectively.

The attractiveness of the firefly is determined by the brightness or the light intensity, which is correlated with the objection function of the algorithm. β can be defined as:

$$\beta = \beta_0 \exp(-\gamma r^m), \text{ with } m \geq 1, \quad (8)$$

where β_0 is the initial attractiveness at $r = 0$.

The distance between two fireflies i and j at x_i and x_j , which is expressed as Euclidean distance, is given as follows:

$$r_{ij} = \|x_i - x_j\| = \sqrt{\sum_{k=1}^d (x_{i,k} - x_{j,k})^2} \quad (9)$$

where $x_{i,k}$ is the k th component of the spatial coordinate x_i of the i th firefly, and d is the dimension number of the problem.

In each generation, the i th firefly is attracted to the brighter firefly j , called as the firefly movement is expressed as:

$$x_i = x_i + \beta_0 \exp(-\gamma r_{ij}^2)(x_i - x_j) + \alpha \varepsilon_i \quad (10)$$

where α is the randomization parameter determined based on the complexity of the problem, which is from the interval $[0,1]$. ε_i is and the vector of random numbers chosen from uniform distribution or Gaussian distribution. The first, second, and third terms are the current position of a firefly, the firefly movement based on the attractiveness, and the random movement of the firefly, respectively.

At the end of the generation, the fireflies are ranked based on their brightness, and the best firefly is chosen. The light intensity of the fireflies is always updated in accordance with the fitness function. As a result, the optimal solution is chosen from the best firefly with the highest brightness.

In this paper, the optimal sizing of SCES is calculated using FA to enhance the transient stability. The objective function is obtaining the highest value of CCT with the minimum SCES. Moreover, the constraint is the limit of SCES value and the power balance. The objective function and the constraint are explained in Eqs. (11) - (13), respectively.

$$\text{Obj. function } (f) = \text{Minimize } (SCES \text{ value}) \quad (11)$$

$$M_i \dot{\omega}_i = P_{mi} - P_{ei}(\delta) - P_{SCES} - D_i(\delta_i) \quad (12)$$

$$P_{SCES,min} \leq P_{SCES} \leq P_{SCES,max} \quad (13)$$

where $P_{SCES,min}$ and $P_{SCES,max}$ are the minimum and the maximum range of SCES power.

For the first step, the SCES value will be randomized for the CCT calculation. CCT value is determined using the critical trajectory method. After that, the FA parameters, such as α , β , and γ , are defined. α has an important role in controlling the random movements to get the solution. A small degree of accuracy for searching the optimal value

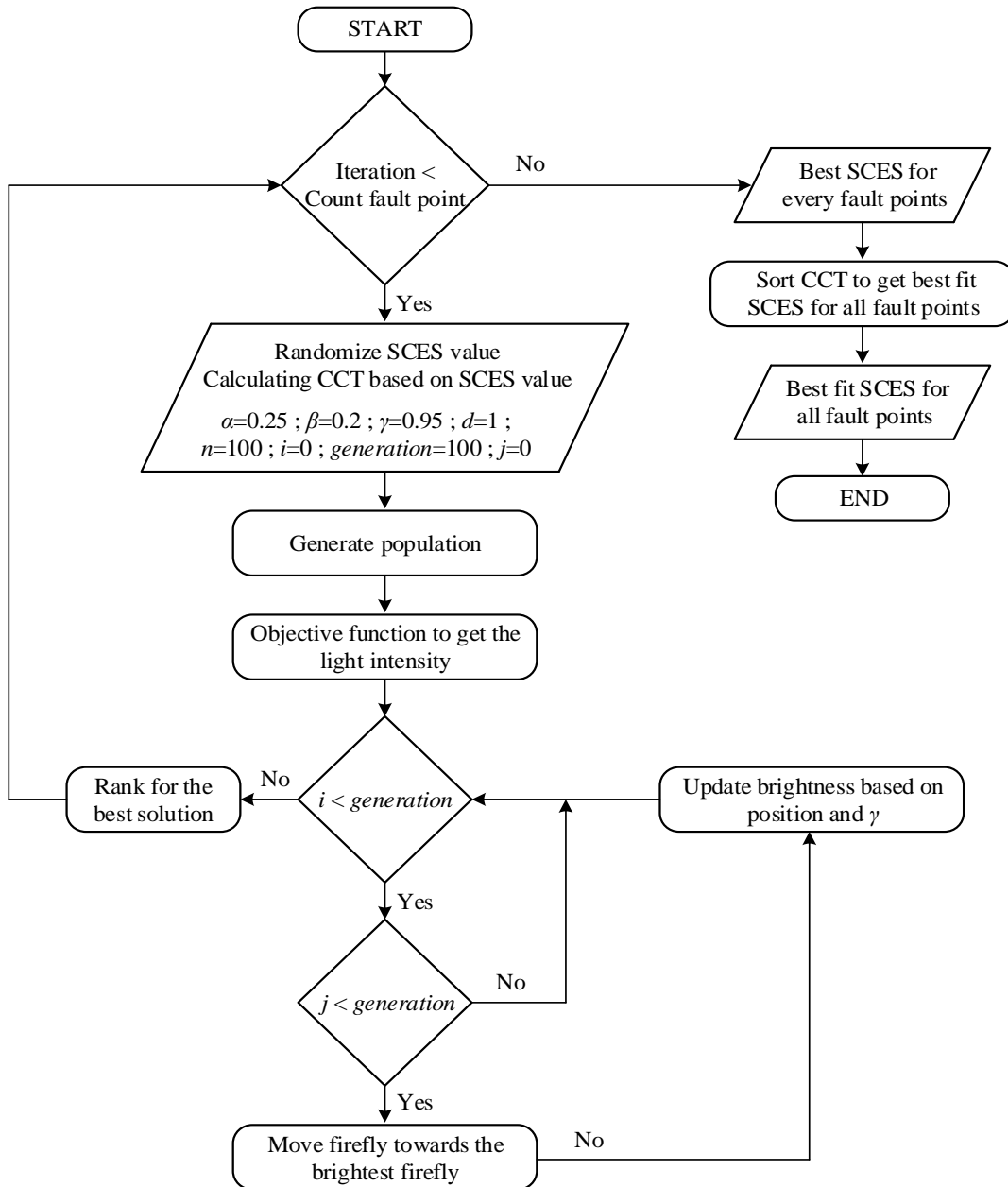


Figure. 2 Flowchart of the proposed method for finding the optimal SCES

will be obtained when using a high value of α because the random displacement becomes too wide. A small value of α is good for the convergence rate towards the desired point. However, α cannot be too small because it can eliminate the random displacement of a firefly. The value of β is determined by the attractiveness of the firefly, which is limited between 0 and 1. A higher value of β will give only a non-cooperative random search.

Furthermore, γ shown the variation of the attractiveness. γ equal to zero means there is no variation or the attractiveness is constant; however, unlimited γ means a completely random search with attractiveness equal to zero. Thus, after tuning the parameter, this paper use α , β , and γ are 0.25, 0.2, and 0.95, respectively. Furthermore, generation=100 is

chosen because it can give the satisfactory performance of the proposed method with minimum computation efforts. After that, the proposed method will calculate the optimal sizing of SCES with a higher value of CCT. Moreover, Fig. 2 shows a detailed flowchart of the proposed method in finding the sizing of SCES.

5. Simulation result and discussion

Simulation using a modified IEEE 3-machine 9-bus system was performed to verify the proposed method. It is assumed that the system is double circuit line transmission, and the three-phase fault is subjected to the system. The critical trajectory method is used to obtain the value of CCT. Each

value of CCT in the modified system will be compared with the base system, a standard system without SCES. Moreover, the FA will be used to get the optimal value of SCES, which has more stability index through the CCT value. The value of SCES is randomly from 0 until 1 in the per-unit base, with the precision 0.001, which is enough for the SCES sizing. Because each fault point has each optimal value of SCES according to the CCT value, the calculation of FA will be carried out in parallel at each fault point to shorten the computation time. After that, FA will give the final result of optimal SCES by comparing the optimal value at each fault point. Furthermore, Lagrange interpolation is used to show the effectiveness of the proposed method.

Table 1 shows the result comparison of CCT value for each fault location after adding the SCES, which is explained in Section 4. It can be concluded that the value of CCT is varies depending on the fault location. The closer the fault location with the generator (Fault A and Fault B), the smaller the CCT value. In fault location A, the CCT system is 0.41173s, which means the system remain stable until 0.41173s before the protection system operates or the disturbance is cleared. However, the system becomes unstable when the disturbances still occur after 0.41173s.

Furthermore, Table 1 shows the comparison of the calculation time between the proposed method with modified Lagrange interpolation. It is seen that the proposed method way faster than the modified Lagrange interpolation. To illustrate the proposed method, the convergence characteristic for the CCT value at each point of fault with the generations as 100 is shown in Fig. 3. In the previous method, the sizing was done manually and only limited to one decimal point per-unit base [25, 26]. However, the proposed method has better precision for the optimal SCES. Using FA, the result shows that the obtained SCES value varies depending on the fault location from 0.120-0.140 p.u. Because of the constraint, which is mentioned in Section 4.3, SCES=0.120 p.u will be chosen.

To check the optimal value of SCES, which is obtained by the proposed method, Table 2 shows the validation of the CCT value. The CCT value from the proposed method will be compared with the base system without SCES. It can be concluded that the CCT value is increasing due to the installation of SCES in the system. For example, at fault point C, the CCT is increasing from 0.3272s to 0.50045s. The deviation of the increment is 0.17325s or around 52.94%. The overall increase in CCT is 0.15766s or around 54.61%. Thus, it can be concluded that the proposed method proved its superiority compared

Table 1. Comparison of the optimal SCES at each fault point using FA

Fault point	SCES (p.u)	CCT (s)	CPU (s)	
			FA	Lagrange
A	0.120	0.41173	93	1030
B	0.121	0.40224	118	1280
C	0.124	0.50045	86	960
D	0.130	0.51945	84	940
E	0.120	0.42902	88	980
F	0.121	0.43644	103	1130
G	0.120	0.43736	128	1380
H	0.140	0.41635	106	1160
I	0.140	0.75727	97	1070

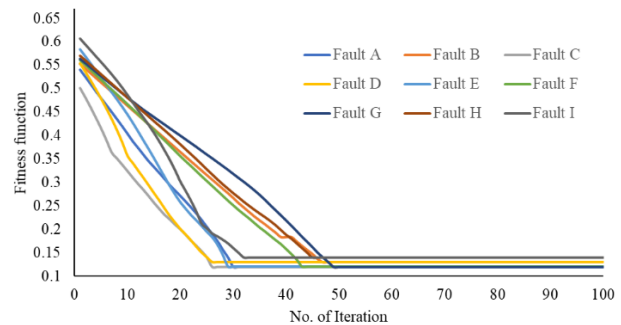


Figure. 3 Comparison of convergence characteristic for the CCT value at each fault point

Table 2. Comparison of the value of CCT with and without SCES 0.12 p.u

Fault point	CCT (s)		CCT increment	
	Without SCES	With SCES = 0.12 p.u	(s)	(%)
A	0.2288	0.41173	0.18293	79.95
B	0.3121	0.40224	0.09014	28.88
C	0.3272	0.50045	0.17325	52.94
D	0.3247	0.51945	0.16763	51.62
E	0.2499	0.42902	0.17912	71.67
F	0.2440	0.43644	0.19244	78.86
G	0.3178	0.43736	0.11956	37.62
H	0.3148	0.41635	0.08804	27.96
I	0.3641	0.75727	0.22583	62.02

with the other existing method in terms of computation time and accuracy.

Moreover, Fig. 4 shows the effectiveness of the proposed method with the bases system. It shows the angular velocity, ω , as the ordinate and the time in second as the abscissa for fault point at A. The base system is shown in the red line and the proposed system using a blue line. It is seen that using SCES in

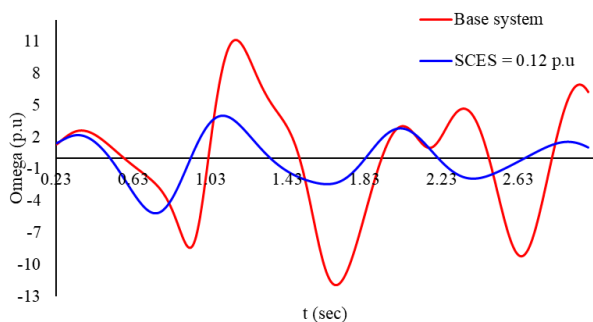


Figure. 4 Angular velocity (ω) and time (s) curve of the generator for fault point at A

the system, the ω can be damped when a fault happens. As a result, the CCT of the system can be increased.

6. Conclusion and future works

Nowadays, the power system is operated near its stability limit due to the imbalance between power demand and supply. Because of that, enhancing system stability becomes one of the main aspects in the power system. In this research work, FA is applied for resolving the optimal sizing of SCES with the objective function of extending CCT. As a result, system stability is enhanced, especially the transient stability.

The proposed method is validated on a modified IEEE 3-machine 9-bus system. At first, the calculation of CCT for the base system without SCES is done using the critical trajectory method. FA is carried out in parallel to obtain the optimal size of SCES at each fault point. As a result, it can shorten the computation time. After that, FA will give the final result of optimal SCES by comparing the optimal value at each fault point. By using the constraint, such as unbalance power and economic sector, the result shows that the optimal sizing of SCES is 0.120 p.u.

Furthermore, the result is compared with the base system to demonstrate the efficiency of the chosen SCES. The overall increase of CCT using 0.120 p.u. as the chosen SCES is 0.15766s or around 54.61%. The obtained outcomes clearly indicate that the system with SCES is found can enhance transient stability. Moreover, the proposed method shows its superiority in computation time and accuracy compared with the existing method. The author believes that the proposed method is potentially implemented in a smart grid system in terms of transient stability enhancement. Further study is also necessary to take into account for bigger transmission system and also implement the other meta-heuristic algorithms.

Conflicts of Interest

The authors identify and declare that there is no any personal circumstances or interest that may be perceived as inappropriately influencing the representation or interpretation of reported research results.

Author Contributions

Conceptualization, Mauridhi Hery Purnomo, Ardyono Priyadi, and Vita Lystianingrum, Talitha Puspita Sari; methodology, Talitha Puspita Sari, Maya Prananda Sari, and Gabriela Evania Sulisty; software, Talitha Puspita Sari, Maya Prananda Sari, and Gabriela Evania Sulisty; validation, Talitha Puspita Sari; formal analysis, Talitha Puspita Sari, Mauridhi Hery Purnomo, Ardyono Priyadi, and Vita Lystianingrum; writing—original draft preparation, Talitha Puspita Sari; writing—review and editing, Mauridhi Hery Purnomo, Ardyono Priyadi, and Vita Lystianingrum, Talitha Puspita Sari; visualization, Talitha Puspita Sari, Maya Prananda Sari, and Gabriela Evania Sulisty; supervision, Mauridhi Hery Purnomo, Ardyono Priyadi, and Vita Lystianingrum; project administration, Talitha Puspita Sari.

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