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Abstract—**The frequency stability enhancement of a power system is proposed in this paper. To enhance the frequency stability, redox flow batteries (RFB) and the thyristor controlled phase shifter are used. Moreover, to get a better performance, the parameter of RFB and TCSC are optimized by the firefly algorithm (FA). Two area load frequency control plant is used as a test system. Time domain simulation is used to assess the performance of the proposed method (adding RFB and TCPS and optimized using FA). From the simulation results, it is found that by installing RFB and TCSC based on FA in the system, the frequency performance can be maintained above the nadir when perturbation emerges.**

Keywords-**Firefly Algorithm (FA), Frequency stability, RFB, TCSC.**

I. INTRODUCTION

The increasing load demand has led to several problems in the power system sector. The problem can come from transmission until distribution sector. The problem in power system is mainly about the stability of the power system. The stability of the power system could also be disturbed by the increasing the capacity of the load. Power system stability itself divided into three categorized which is rotor angle stability, voltage stability, and frequency stability. Rotor angle stability is related to the ability of the power system to maintain stable condition after being subjected to a small perturbation. While voltage stability is the ability of the power system to maintain reactive power in the system. Furthermore, frequency stability related to the ability of the power system to maintain the balance between generating capacity and load capacity [1]. Hence, the frequency stability of the systems is influencing by the increasing load demand capacity.

Maintaining the frequency performance of the system can be done by controlling the generating as well as load automatically. This method commonly called load frequency control (LFC) [2]. The procedure of LFC is putting a feedback signal of a frequency of the system and pass it through the governor controller. Generally, the governor controller is a simple integral control. However, only used the integral controller to maintain the frequency stability is out of date. Hence, additional devices such as flexible ac transmission systems (FACTS) devices can be considered to enhance the frequency performance of the system.

There have been many types of FACTS devices that already implemented in the practical scenario as well as in the research paper [3-8]. Among them, TCPS is becoming more popular to enhance the frequency stability of the systems [6]. However, due to the increasing load demand as well as the uncertainty of the load, TCPS is not enough to maintain the frequency between the requirements. Hence, it is essential to utilize additional devices to handle the uncertainty of the load demand.

Energy storage can be used as additional devices in the power system. These devices have been shown a better performance as an additional controller to provide as well as store energy when the load changing emerge. Energy storage has shown a promising result for solving stability issue of power system such as rotor angle, voltage as well as frequency stability [9-19]. In recent years, there is a new energy storage that has shown a better response for providing energy in fast response called redox flow batteries (RFB) [17, 20]. This energy storage utilizes the ability of sulfuric acid and vanadium ion for storing electrical energy in the large amount [17, 20]. The major problem here is how to design and optimize the parameter of TCPS and RFB. Designing TCPS and RFB parameters cover a complex mathematical calculation. Hence, artificial intelligence techniques can be used to simplify the problems.

Artificial intelligence can be divided into three categorize, namely artificial neural network (ANN), fuzzy logic system, and metaheuristic algorithm. Metaheuristic algorithm has shown a better performance for solving optimization method. There is a lot of type of metaheuristic algorithm that has been used to solve optimization problems in the last few decades. The application of metaheuristic for solving optimization problems has been developed significantly over the past few decades as reported in [21-25]. The application of cuckoo search algorithm to tuning the parameter of SMES and CES is reported in [21]. In [22], the small disturbance angle stability

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problems of power systems can be handled properly by utilizing cuckoo search algorithm. The application of particle swarm optimization and differential evolution algorithm for designing the blade pitch angle wind turbine is reported in [23]. The application of imperialist competitive algorithm for solving frequency stability problems in small-scale power systems is reported in [24]. Furthermore, the application of craziness particle swarm for designing dual input of power system stabilizer is reported in [25]. Among them, firefly algorithm is one of the newest metaheuristic algorithms that becoming favorable due to the fast computational and simple algorithm compared to the other algorithm [26]. Hence, the novelty of this paper is proposing a method to enhance the frequency stability of a power system using coordinated control between RFB and TCPS. To get better coordination, the parameter of RFB and TCPS are optimized by FA.

II. FUNDAMENTAL THEORY

A. *Load Frequency Control*

In power system domain, the frequency is one of the essential parameters in addition to the voltage parameters. Controlling the frequency of the power system can guarantee the constant rotation of the synchronous machine. This constant rotation is important for obtaining desired system performance. In large-scale interconnection system, large and small power plants are connected to each other. All machine operate in synchronous condition so that the generators must operate at the same frequency [27].

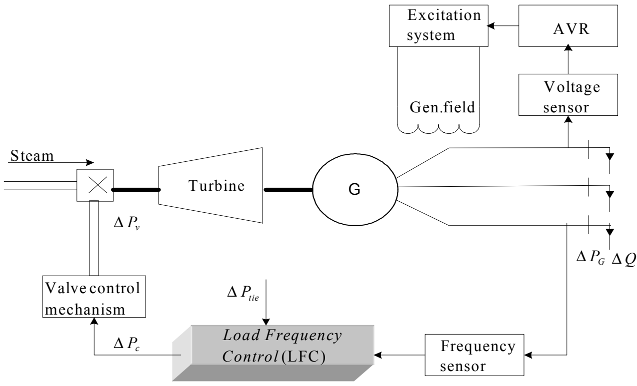

Fig. 1 Schematic diagram of LFC.

The power supplied by each generator is different and always evolves according to the variation of load that emerges over the time. The ability of the generator to respond to the load fluctuation is very important. In an interconnected power system, generation in each area is controlled to maintain scheduled power changes, at which point the frequency becomes very important as a representation of the active power fluctuations of the system. Generation and frequency settings are known as load frequency control (LFC) [27, 28].

Frequency control generally has the goal of making the system frequency stable even with the various loads that emerge at any time. With steady state frequency regulation, the balance of the assembly system to the load is better. Furthermore, the power flow in the interconnected power generating unit remains at the level specified by each capability. Fig. 1 illustrates the frequency settings on the electric power system in the form of frequency control [27, 28].

In a power system, controlling the frequency can be done by setting the active power on the machine. The provision of active power must be adjusted to the need for active load power. This adjustment is made by adjusting the coupling of the generator so there is no waste of power usage. Based on the Newton law, the relations between mechanical coupling with the rotation of the generator can be described using (1) [29].

$$(T_G - T_B) = H\frac{d\omega}{dt} \tag{1}$$

In (1), T_G and T_B are the generators and load coupling, while H and ω are inertia and rotor speed of the generator. Hence, the frequency of the system can be presented as given in (2) [29].

$$f = \frac{\omega}{2\pi} \tag{2}$$

Hence, it can be stated that the frequency control can be done by arranging the fuel provision in the thermal power system. The frequency is decreased when the active power generated is not enough to supply the load demand. In contrast, the frequency is increased when there is surplus active power in the system. The deviation of frequency can be calculated using (3) [29].

$$\begin{aligned} &T_G - T_B = \Delta T < 0, \text{ hence } \frac{d\omega}{dt} < 0 \text{ , \textit{frequency} decreased} \\ &T_G - T_B = \Delta T > 0, \text{ hence } \frac{d\omega}{dt} > 0 \text{ , \textit{frequency} increased} \end{aligned} \tag{3}$$

B. *Redox Flow Batteries*

RFB stores energy in the form of an electric field in the sulfuric acid with vanadium ions. The device comprises a voltage source converter (VSC), converter controller and sulfuric acid with vanadium ions as shown in Fig (2) [30-32]. The mathematical model of RFB that use in this paper is described in (4) [30-32].

$$\Delta P_{rfb} = \left\{\omega_{generator}K_{rfb} - \left(\frac{K_{ri}}{1+sT_{ri}}\right)\right\}\left(\frac{1}{1+sT_{di}}\right) \tag{4}$$

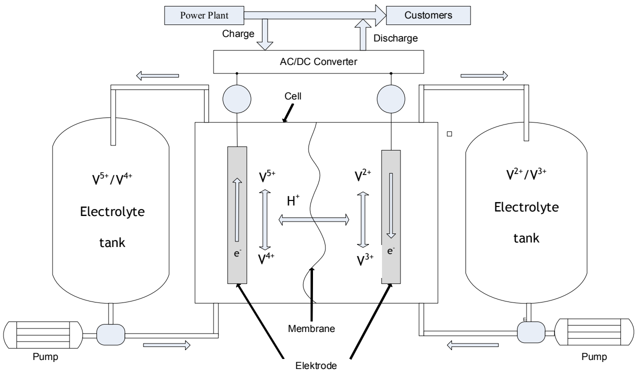

Fig. 2 Schematic diagram of RFB.

C. Thyristor Controlled Phase Shifter

Controlling the power flow between tie-line can be done by installing the TCPS in series with tie-line as depicted in Fig. 3. By controlling the power flow in the tie line, the frequency of the system can be also controlled. Furthermore, the mathematical representation of the power flow deviation in the tie line without TCPS can be described as given (5) [33].

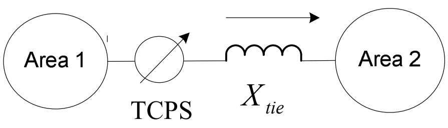

Fig. 3 Schematic diagram of TCPS connected to tie line.

$$\Delta P_{12}{}^{o} = \frac{2\pi T^{o}}{s}\left(\Delta f_1 - \Delta f_2\right) \tag{5}$$

In (5), T^o, P_{12o}, f_1, and f_2 are the synchronous coefficient transmission line without TCPS, power flow deviation, frequency deviation in area 1 and area 2. The mathematical representation of power flow deviation with TCPC can be described using (6).

$$P_{tie} = \frac{|V_1||V_2|}{X_{12}}\sin\left(\delta_1 - \delta_2 + \varphi\right) \tag{6}$$

In (6), P_{tie} is the power in tie line with TCPS in the transmission line, while ϕ is the variable of voltage angle that can be controlled by TCPS. Moreover, the mathematical representation of power flow in the tie line when small perturbation occurs can be described using (7).

$$\Delta P_{tie} = \frac{|V_1||V_2|}{X_{12}}\cos\left(\delta_1^o - \delta_2^o + \phi^o\right)\left(\Delta\delta_1 - \Delta\delta_2 + \Delta\phi\right) \tag{7}$$

In (7) $\delta_1{}^o$ is the nominal condition of voltage angle before the disturbance, while $\Delta\delta_1$ is the voltage deviation when perturbation emerges. Moreover, the mathematical representation of synchronization coefficient between area can be presented as (8). Hence, P_{tie} can be calculated using (9) and (10). Furthermore, the Laplace representation of equation (10) can be presented as (11).

$$T_{12} = \frac{|V_1||V_2|}{X_{12}}\cos\left(\delta_1^o - \delta_2^o + \phi^o\right) \tag{8}$$

$$\Delta P_{tie12} = T_{12}\left(\Delta\delta_1 - \Delta\delta_2 + \Delta\phi\right) \tag{9}$$

$$\Delta P_{tie12} = T_{12}\left(\Delta\delta_1 - \Delta\delta_2\right) + T_{12}\Delta\phi \tag{10}$$

$$\Delta P_{tie12} = \frac{2\pi T_{12}}{s}\left[\Delta F_1(s) - \Delta F_2(s)\right] + T_{12}\Delta\phi(s) \tag{11}$$

From equation (11), the phase shifter ($\Delta\theta$) angle can be used to control the tie-line power flow. It can be assumed that input of TCPS is an error(s), while the K_θ is TCPS gain controller. Furthermore, the phase shifter of TCPC can be calculated using (12).

$$\Delta\varphi(s) = \frac{K_\phi}{1 + sT_{PS}}\Delta Error_1(s) \tag{12}$$

In (12), T_{PS} and $\Delta Error_1(s)$ are the time constant of TCPS and the input signal from TCPS. Furthermore, by considering equation (11) and (12), the power flow in tie-line can be presented as given in (13) [33].

$$\Delta P_{tie12} = \frac{2\pi T_{12}}{s}\left[\Delta F_1(s) - \Delta F_2(s)\right] + T_{12}\frac{K_\phi}{1 + sT_{PS}}\Delta Error_1(s) \tag{13}$$

III. DESIGN RFB AND TCPS BASED ON FA

Firefly algorithm (FA) is one of the algorithms in the field of metaheuristic approaches. In the heuristic approach, there is the term of swarm intelligence which is defined as a design algorithm or problem-solving tools inspired by the collective social behavior of insect colonies and animal colonies. Hence, FA can be categorized as swarm intelligence [34].

FA is a metaheuristic algorithm inspired by the flashing behavior of fireflies. This algorithm was developed by Dr. Xin-She Yang at Cambridge University to solve optimization problems. There are about two thousand species of fireflies and most of the fireflies produce a momentary and rhythmic blink of light, and for certain species, the blinking pattern is very unique. This light flicker is produced from the bioluminescence process. The actual function of this signal system is still being discussed. However, there are two basic functions of the blinking behavior of fireflies that are to attract the attention of their mates and to attract the attention of their prey [35].

The general formulation of this algorithm is presented together with mathematical modeling analysis to solve problems with the purpose of equivalence function. FA has three important parts as described in the following rules [36]:

- The fireflies sex is ignored, so regardless of their sex, fireflies will be attracted to each other.
- The attraction is proportional to the brightness of the fireflies. Fireflies with lower brightness levels will be attracted and move to fireflies with higher brightness. Brightness may decrease with increasing distance and the absorption of light due to air factor. If there are no fireflies with the most brightness light, the fireflies will move randomly.

- The objective function of the particular problems can be determined as the brightness or intensity of the firefly.

There are two things that are related and very important in FA namely light intensity and attractiveness function. In this case, we assume that the attractiveness is influenced by the degree of light intensity. The degree of light intensity on a firefly x can be stated as (14).

$$I(x) = f(x) \tag{14}$$

In (14), *I* indicated the level of light intensity on *x* fireflies that is proportional to the solution of the objective function *(f(x))*. *β* is the attractiveness coefficient that has relative value due to the light intensity that must be seen and assessed by other fireflies. Hence, the result of the assessment will differ depending on the distance between the fireflies. In addition, the light intensity will decrease from the source due to the air factor (γ). Hence, the mathematical representation of the attractiveness function is presented in (15).

$$\beta(r) = \beta_0 * \exp\left(-\gamma r^m\right), \left(m \geq 1\right) \tag{15}$$

The distance between fireflies *i* and *j* at the locations *x*, *xi* and *xj* can be determined when they are placed at the point where fireflies are dispersed randomly in the Cartesian diagram as presented in (16). Where the different location of firefly *i* to firefly *j* is the distance between those two (*rij*).

$$r_{ij} = \sqrt{\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2} \tag{16}$$

The movement of fireflies that move towards the best level of light intensity can be described as (17) [34-36].

$$x_i = x_i + \beta_0 * \exp\left(-\gamma r_{ij}^2\right) * \left(x_j - x_i\right) + \alpha * \left(rand - \frac{1}{2}\right) \tag{17}$$

In (17), x_I indicated the initial position of fireflies located at *x*, while alpha is a variable that has a range between 0 and 1. All the variables formed on (17) ensure the fast algorithm work toward the optimal solution [36].

In this paper, FA is used to optimize the parameter of RFB and TCPS to mitigate the low-frequency oscillation on the power system. To find the optimal parameter of RFB and TCPS, comprehensive damping index is used as the objective function of the FA which can be calculated using (18) [37].

$$CDI = \sum_{i=1}^{n} \left(1 - \xi_i\right) \tag{18}$$

IV. RESULTS AND DISCUSSIONS

The case study is carried out using MATLAB/SIMULINK environment. Two areas load frequency control of the power system is considered in this paper as the test system. A modification has been made by adding RFB in area 1 and installing TCPS in the tie line between area 1 and area 2. Fig. 4 shows the schematic diagram of the test system. Observation of a linear time domain is conducted to analyze the frequency response of the system.

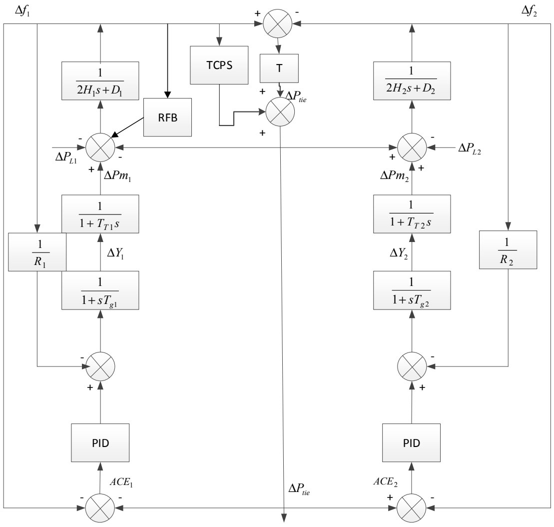

Fig. 4 Test systems.

To analyze the performance, a perturbation is made in the system by giving step input of load change in area 1. Figs. 5 and 6 show the frequency response in area 1 and area 2, while Fig. 7 illustrates the tie line power flow response. It is monitored that, when the load demand is decreased, the frequency response in area 1 and area 2 are started to accelerate. It is noticeable that, due to the accelerated frequency in area 1 and area 2, the tie line power flow is also increased.

Tables 1 and 2 depict the detailed featured of overshoot and settling time of frequency response in area 1 and area 2. While Table 3 shows the detailed featured of overshoot and settling time of tie-line power flow. Moreover, the overshoot and settling time for frequency in area 1 and area 2, as well as tie-line power flow, is decreased when RFB and TCPS are installed in the system. This condition could happen because of RFB is operate in charging condition. Hence, the surplus of electrical energy from the system due to the decreasing of load demand can be stored by RFB (RFB works as additional load). Moreover, TCPS provide the accurate phase shifter to stabilize the tie line power flow. Furthermore, the best response is shown by the system with the proposed response (adding RFB and TCPS based on FA) indicated by small overshoot and fastest settling time. It should be noted that the base case in this study is two area power system with integral control as the governor controller. The base case data is based on the existing scenario in reference [27].

As reported in [29], the frequency of the system has to be back in the initial condition not more than 10 minutes. As shown in Figs. 5-7, the frequency back to normal less than 25 seconds. Hence the standard minimum of frequency settling time is achieved in all of the cases. Furthermore, 10 % of the load has to be shed if the deviation the frequency is more than ± 0.8 Hz or pu. If the load shedding procedure emerges, it is not good for the reliability of systems. It can be seen in Fig. 5 and table 1, the overshoot frequency on the base case and systems with TCPS are more than 0.8 pu. It is also observed that a system with RFB, a system with RFB and TCPS and the proposed system can achieve the overshoot of the frequency. Furthermore, it is also noticeable that the proposed systems provide the best frequency response compared to the other cases in this study. It is also noticeable that the proposed system could only reduce the frequency overshoot. This is acceptable as the settling time of the system is already achieved the standard in the base case.

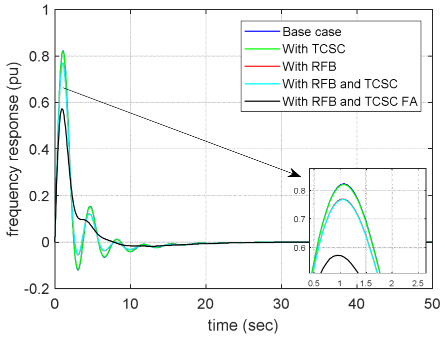

Fig. 5 The frequency response in area 1.

Table 1 Detailed features of Fig.5

Cases	Overshoot (pu)	Settling time (s)
Base case	0.8222	>25
With TCPS	0.8199	>25
With RFB	0.7691	>25
RFB TCPS	0.7669	>25
Proposed method	0.5731	>25

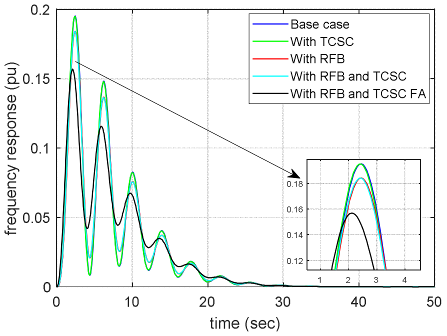

Fig. 6 The frequency response in area 2.

Table 2 Detailed features of Fig. 6.

Cases	Overshoot (pu)	Settling time (s)
Base case	0.1951	>25
With TCPS	0.1949	>25
With RFB	0.1841	>25
RFB TCPS	0.1839	>25
Proposed method	0.1568	>25

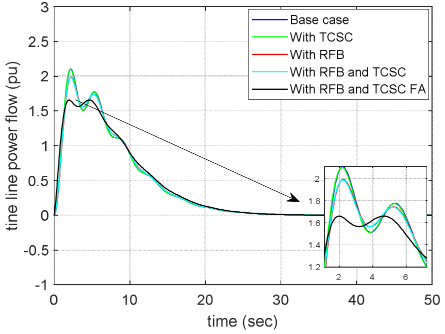

Fig. 7 The tie line power flow response.

Table 3 Detailed features of Fig. 7.

Cases	Overshoot (pu)	Settling time (s)
Base case	2.102	>25
With TCPS	2.099	>25
With RFB	1.989	>25
RFB TCPS	1.985	>25
Proposed method	1.657	>25

V. CONCLUSIONS

This paper proposed a method for enhancing the frequency stability of a power system by employing coordinated control between RFB and TCPS based on FA. From the simulation results, it is found that by installing RFB and TCPS as well as tune the parameter of the devices simultaneously, resulting in the enhancement of the power system frequency response. It is monitored that RFB enhances the frequency response of the system by releasing energy when the load demand is increased and storing the energy when the load demand is decreasing. The best performance is provided by the system with RFB and TCPS tuned with FA, indicated by the smallest overshoot. Considering renewable energy integration and analyses the impact of frequency stability of a power system can be used as the further research.

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