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Small-Disturbance Angle Stability Enhancement using Intelligent Redox Flow Batteries

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***Abstract*— Small-disturbance angle stability or low-frequency oscillation is one of the important stability in the power system. Although damper windings and power system stabilizer (PSS) have been proved to stabilize and improve small-disturbance angle stability. However, due to increasing demand in the recent years, adding redox flow batteries (RFB) as additional devices is crucial. This paper investigates, the utilization additional devices called RFB to enhance the small-disturbance angle stability in the power system. Furthermore, ant colony optimization (ACO) method is used to tune RFB parameter. To analyze the stability improvement on the power system, single machine infinite bus is used as a test system. Eigenvalue and time domain simulation is used to examine the behavior of the investigated system. From the simulation, it is found that by installing RFB in the system, the small-disturbance angle stability of power system is improved and ACO can be a solution of tune RFB parameter.**

Keywords—Ant colony optimization (ACO), redox flow batteries (RFB), small-disturbance angle stability.

I. INTRODUCTION

In recent years, the demand for electric power grows significantly due to human population growth. The power system load becoming larger and uncertainty over the past decade. This large and uncertain load can lead to unstable condition on the power system. Among the unstable condition, small-disturbance angle stability or low-frequency oscillation is becoming a particular concern in power system.

Small-disturbance angle stability has a frequency range of 0.1 to 2 Hz [1]. If this oscillation not well damped, the magnitude may grow larger and lead to synchronism losses [2]. Generally, this problem is primarily dealt by installing damper windings in the rotor of the generator of by adding power system stabilizer (PSS) in excitation system. However, due to increasing load and the uncertainty characteristic of the load adding damper windings and PSS is not enough. Hence, another device such as energy storage system can be consideration of stabilizing and enhance small-disturbance angle stability.

There are numbers of energy storage in the last decade such as capacitor energy storage [3]; superconducting magnetic energy storage [4, 5]; flywheel energy storage [6]; battery energy storage [7-9]. Among of energy storage type, redox flow batteries (RFB) becoming popular due to the fast response of the device. However, due to a large-scale system, increasing and uncertain load demand, the complexity of the system increase significantly. Therefore, parameter tuning of RFB using an intelligent method such as metaheuristic algorithm is crucial.

A metaheuristic is formally defined as an iterative generation process which guides a subordinate heuristic by combining intelligently different concepts for exploring and exploiting the search space; learning strategies are used to structure information to find efficiently near-optimal solutions [10]. Metaheuristic means to procedure high-level algorithm to find, create or choose with lower rates that can provide a good solution to optimization problems. In designing metaheuristic algorithm, nature is one of the biggest inspiration for scientist [11]. For example genetic algorithm, inspired by Darwin biological systems, particle swarm optimization based on the behavior of swarm birds, differential evolution algorithm inspired by recurrence cycle, imperialist competitive algorithm inspired by imperialist competitive, artificial immune systems inspired by antibody systems, as well as ant colony optimization (ACO) inspired by ants activity to find food [11-16]. ACO is proven to be one of the best optimization approaches in recent years. ACO has solved many optimization problems such as traveling salesman problems.

This paper explained the enhancement of small-disturbance angle stability using redox flow batteries. To get the better performance, ACO is chosen as optimization method to tune RFB parameter. The rest of the paper is organized as follows: Section II briefly explain about power system model, RFB dynamic model and fundamental theory of ACO. Small-disturbance angle stability analysis is described in Section III. Section IV shows the modal analysis and time domain simulation. Section V highlights the contribution, conclusions and future directions of the research.

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II. FUNDAMENTAL THEORY

A. Power System Model

Small-disturbance angle stability in the power system can be analyzed through single machine infinite bus model [17]. Although only local phenomena that can be captured, this system can be clearly visualized the dynamic behavior of power system. For this research nine-order model of single machine infinite bus is used as test system [17]. The Simulink representation of the single machine infinite bus is shown in Fig. 1.

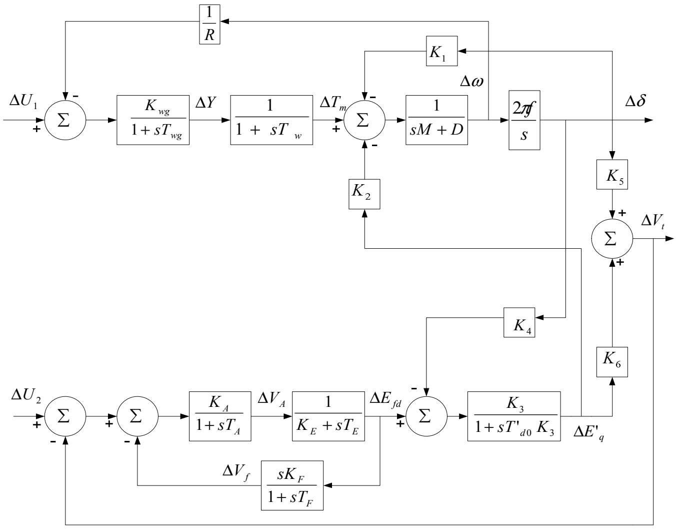

Fig. 1. Single machine infinite bus simulink model [17].

B. Redox Flow Batteries Model

Energy storage application becoming popular in recent years due to increasing demand, integration of renewable energy sources and development of power electronics devices. Among of the energy storage type redox flow batteries (RFB) become widely used in power system. RFB provide quick response and higher capacity than regular battery [18, 19]. RFB consist of sulfuric acid with vanadium ions, voltage source converter (VSC) dynamic and associated controller as depicted in Fig. 2. For this research, RFB modeled into the dynamic model as described in (1) [18, 19].

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

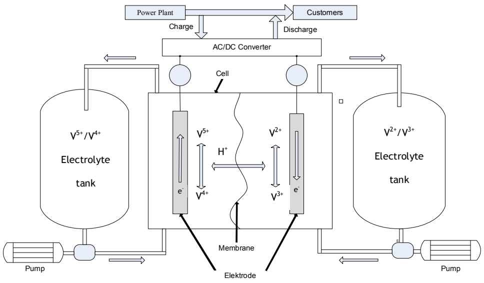

Fig. 2. Schematic diagram of RFB [18, 19].

C. Ant Colony Optimization

Ant colony optimization is an algorithm inspired by ants to search optimal value from an optimization problem. ACO first introduced by Marco Dorigo around 1990 [20-28]. ACO is inspired by ant behavior to find the shortest path between the nest and food. This algorithm has been frequently applied to traveling salesman problems [20-24]. At ACO, among ants exchanging information using pheromone that is placed on the path. The path has a pheromone with a large quantity of appeal to the ants. Every time the ants make a tour, ants leaving pheromone on each path impassable [20-24]. Levels of pheromone in the path of the ant will increase while the pheromone levels on the track were not covered, ants will undergo evaporation. The shortest path will often bypass by ants so that the levels of pheromone on the path of getting grow and attract others ant to pass through the path. Fig. 3 shows the ACO's flowchart [20-24].

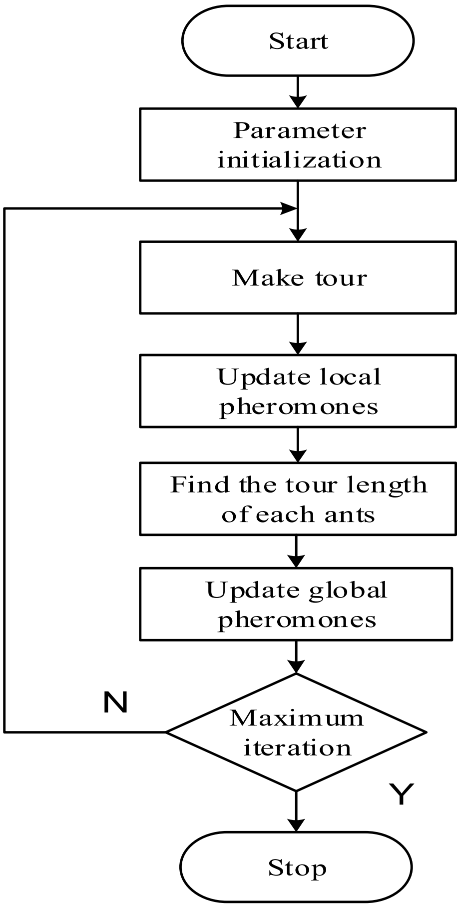

Fig. 3. Flowchart ACO [20-24].

Ant does a tour based on a probabilistic function with two important steps. First, compute nodes that have visited the accumulation is calculated as a distance of a tour. Second, ant detects the pheromone left by other ants [20-24]. The ants then choose the cities *j*, which is in the list of candidates by following a transition rule in (2).

$$j=\begin{cases}\arg\max_{u\in J_l^k}\{[\tau_{iu}(t)][\eta_{iu}(t)]^{\beta}\} & ,if\ q\leq q_0\\ J & ,if\ others\end{cases} \tag{2}$$

$$P_{iJ}^{k}=\frac{[\tau_{iu}(t)][\gamma_{iu}(t)]^{\beta}}{\sum_{l\in J_l^k}[\tau_{il}(t)][\gamma_{il}(t)]^{\beta}} \tag{3}$$

Where τ, η, q are pheromones, the inverse of the distance between two nodes and a random variable uniformly distributed in the ranges of 0-1 [20-24]. While q_0 and J corresponded to a parameter that can be tuned on the interval 0-1 and a list of candidates and selected based on (3) respectively [20-24]. There are two ways to update pheromone in ACO; one is local update the other is global update. The local update is done when the ants pass one-track segment. This process can be determined using (4). Global update is done when all the ants have been doing the tour. Global update only performed in pathways that by-passed by ants [20-24]. This step can be derived using (5).

$$\tau_{ij}(t)=(1-\rho)\tau_{ij}(t-1)+\rho\tau_0 \tag{4}$$

$$\tau_{ij}(t)=(1-\rho)\tau_{ij}(t-1)+\frac{\rho}{L_{best}} \tag{5}$$

Where ρ is constant evaporation. While τ_0 and L_{best} are the initial value of the pheromone and the best tour respectively.

III. SMALL-DISTURBANCE ANGLE STABILITY

Small-disturbance angle stability is the ability of power system to maintain the stable condition after being subjected by small perturbation [29]. This instability emerges due to lack of damping in the system [29]. If this stability is not well maintained, it may lead to unstable condition, and it will cause partially or fully black out of the system [30]. There has been many accidents related to small-disturbance angle stability, such as in northeast United States blackout in August 2003 and India black out on July 2012 [31].

Small-disturbance angle stability can be a local and global phenomenon. A local phenomenon related with small parts of power system again the rest of the system in one particular area. The frequency oscillation of this problems is around 0.7-2 Hz [30]. While global phenomenon or well known as inter-area oscillation is associated with large groups of generation against each other. The frequency oscillation of this particular problems is 0.1-0.7 [30]. For small-disturbance angle stability, eigenvalue analysis is one of the methods to analyze the problems. To find eigenvalue of the system, state space representation has to be conducted. State space representation of power system can be determined using (6) and (7) [32].

$$\Delta\dot{x}=A\Delta x+B\Delta u \tag{6}$$

$$\Delta y=C\Delta x+D\Delta u \tag{7}$$

Where Δx is a linearized vector of state variables. Δy represents a linearized vector of algebraic variables. Δu corresponded to the input vector. *A* and *B* are planted matrix and control or input matrix, respectively. While output matrix and feedforward matrix corresponded to *C* and *D,* respectively [32]. Through the matrix system A, eigenvalue can be determined using (8).

$$\det(\lambda\boldsymbol{I}-\boldsymbol{A})=0 \tag{8}$$

Where I is the identity matrix, and λ is eigenvalues of matrix A. Moreover, complex eigenvalue can be stated as (9). Then to calculated frequency oscillation on power system, (10) can be used [32].

$$\lambda_i=\sigma_i\pm j\omega_i \tag{9}$$

$$f_i=\frac{\omega_i}{2\pi}\ (Hz) \tag{10}$$

Where λ_i is Eigenvalue number-*i*. While σ_i and ω_i are real component from eigenvalue number- i and imaginary part from eigenvalue number- *i*. Eigenvalue imaginary part is a component of frequency oscillation. The other way around, real parts of eigenvalue corresponded to damping of the system [32]. Damping ratio of the system can be defined using (11).

$$\xi=\frac{\sigma_i}{\sqrt{\sigma_i^2+\omega_i^2}} \tag{11}$$

IV. RESULT AND DISCUSSION

The case study was carried on MATLAB/SIMULINK environmental. The test system is single machine infinite bus system with RFB installed in the transmission system. The purpose of using single machine infinite bus is to analyses the dynamic behavior of power system on local phenomenon only. If the interest is the dynamic behavior of local phenomenon only than single machine infinite bus is the best system. For small-disturbance angle stability the domain of the simulation was on per unit, so all of the value in the simulation was in per unit domain. Fig. 4 shows the schematic diagram of the test system. ACO was used to optimize the parameter of RFB. Fig. 5 illustrates the convergence curves of ACO. It was clearly shown that after 39 iterations, ACO found the convergence value.

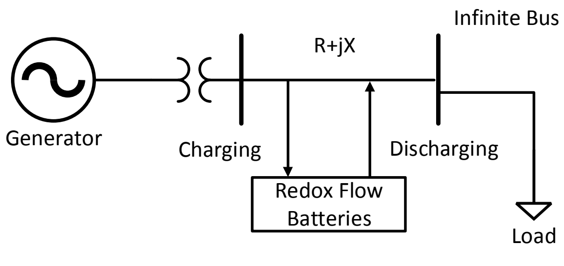

Fig. 4. Schematic diagram of the test system.

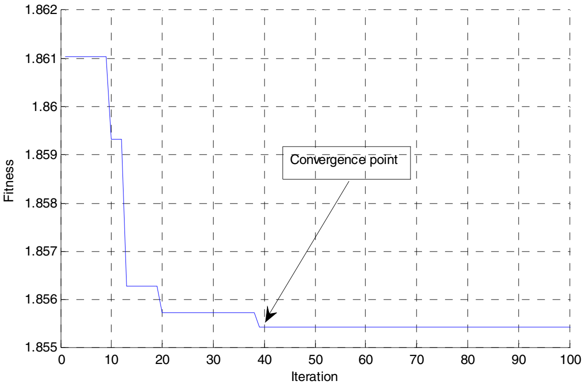

Fig. 5. Convergence graph of ACO.

It was shown in Table 1 that, the electromechanical mode of the system with optimal RFB is more minus than another system. It was also found that the damping of the RFB was the highest compared with other as shown in Fig 6 where the minimum damping standard was 0.05. To validate the eigenvalue in Table 2, time domain simulation was carried on. To observe the response, a small disturbance was made by giving 0.05 step input. From the time domain simulation depiction in Fig 7-9 (rotor speed, rotor angle, terminal voltage), SMIB with optimal RFB has the less oscillatory condition with small overshoot and fastest settling time. Table 2-4 (rotor speed, rotor angle, terminal voltage) show the overshoot and settling time comparison of the investigated system.

TABLE I. EIGENVALUE COMPARISON

Mode	Test System		
	Without RFB	***With RFB***	***Optimal RFB***
Electromechanical	-0.18+8.8i	-0.26+8.8i	-0.51 + 8.9i

Fig. 6. Damping ratio comparison.

The maximum rotor speed overshoot for small-disturbance angle stability was 0.015 pu while the settling time was less than 20 sec. Even the system without a controller has overshoot less than standard as shown in Table 2 and fig 7. However, the settling time of the rotor speed exceeded the minimum standard. The best performance was a system with optimal RFB with the smallest overshoot and fastest settling time or did not exceed the minimum standards settling time.

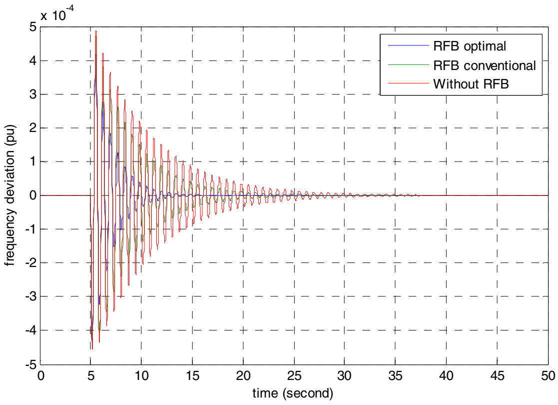

Fig. 7. The oscillatory condition of rotor speed.

TABLE II. OVERSHOOT AND SETTLING TIME OF ROTOR SPEED

Mode	Test System		
	Without RFB	***With RFB***	***Optimal RFB***
Overshoot (pu)	0.0004878	0.0004712	0.0004177
Settling time (sec)	>40	>30	>20

For small-disturbance angle stability, all the domain was in per unit. For rotor angle, there was not maximum standard overshoot only the settling time. The settling time response could not exceed than 20 sec. The best performance that satisfies the standard was a system with optimal RFB as shown in Fig. 8 and Table 3.

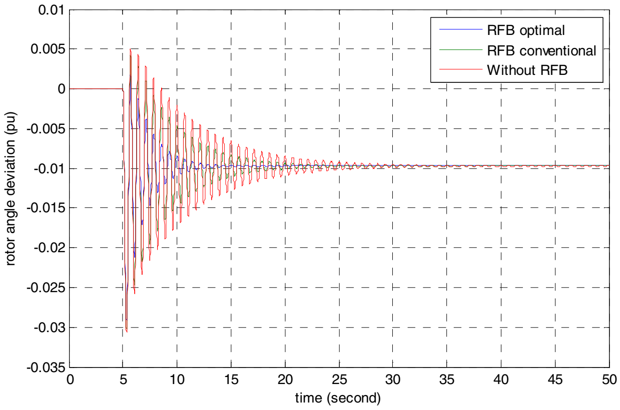

Fig. 8. The oscillatory condition of rotor angle.

TABLE III. OVERSHOOT AND SETTLING TIME OF ROTOR ANGLE

Mode	Test System		
	Without RFB	***With RFB***	***Optimal RFB***
Overshoot (pu)	-0.03057	-0.03024	-0.02912
Settling time (sec)	>40	>30	>20

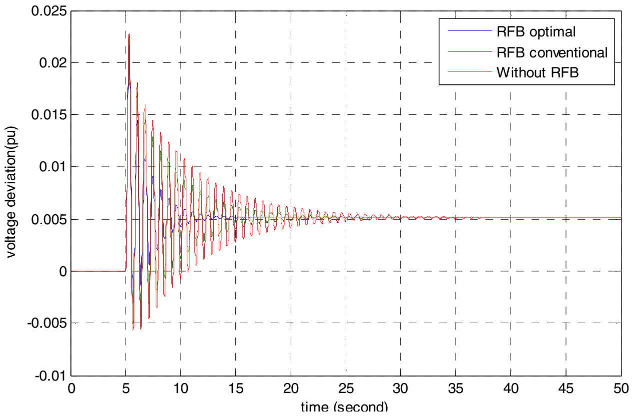

Fig. 9. The oscillatory condition of terminal voltage.

TABLE IV. OVERSHOOT AND SETTLING TIME OF TERMINAL VOLTAGE

Mode	**Test System**		
	Without RFB	***With RFB***	***Optimal RFB***
Overshoot	0.02272	0.02247	0.02163
Settling time	>40	>30	>20

For small signal stability or small-disturbance angle stability maximum overshoot of the voltage was 5% and the settling time could not exceed than 20 sec. From the table 4, it was shown that all of the overshoot of the cases were less than the maximum overshoot allowed. However, the only system with optimal RFB that satisfy the standard of settling time signal in small-disturbance angle stability.

V. CONCLUSIONS

This paper investigated the enhancement of small-disturbance angle stability using intelligent RFB based on ACO. From the case study, it is found that adding RFB have influence in electromechanical mode. It was also found that RFB provides better performance in term of damping, overshoot and settling time.

Ant colony can provide the optimum values of RFB parameter. Further research is required in a large system such as multi-machine power system to analyze the RFB impact in local and inter-area oscillation. It also suggested, RFB installed in a system with renewable energy sources or installed in power system based on renewable energy sources. Utilizing another algorithm such as firefly algorithm, bat algorithm can be a consideration.

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