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Mitigation of Power System Oscillations Using STATCOM-Based PDD Damping controller

***Abstract**. The menace of losing stability following a disturbance is one of the results of such a stressed system. Shunt Flexible AC Transmission System (FACTS) namely static synchronous compensator (STATCOM) can play important role to enhance power system stability. To more reduction of power system oscillations, a supplementary damping controller is very essential for STATCOM. A maiden attempt has been made to implement Proportional-Double Derivative (PDD) structure as a supplementary damping controller for STATCOM. To demonstrate robustness of proposed damping controller, it has been compared with Proportional-Integral (PI), Lead-Lag (LL) and Proportional-Integral-Derivative (PID) controllers. Also, dynamic performance of these controllers is evaluated under three different conditions of disturbance in Single-Machine Infinite-Bus (SMIB) power system. The Real Coded Genetic Algorithm (RCGA) optimization technique due to have high sufficiency to solve the very non-linear objective is applied for solution of the optimization problem. The obtained results of the power system stability improvement in SMIB power system reveal the robustness of STATCOM-based PDD damping controller.*

***Streszczenie.** W artykule przedstawiono implementację regulatora proporcjonalno-podwójnie-różniczkującego (PDD), do tłumienia oscylacji w kompensatorze STATCOM. Dokonano porównania działania proponowanego regulatora z klasycznymi strukturami jak: PI, LL, PID. Przeprowadzono badania w trzech różnych stanach dynamicznych. Do optymalizacji regulatora wykorzystano algorytm genetyczny RCGA. Wyniki badań potwierdziły, zwiększoną stabilność systemu, a co za tym idzie niezawodność i skuteczność działania regulatora. (**Redukcja oscylacji mocy przy użyciu kompensatora STATCOM – wykorzystanie regulatora PDD**)*

Keywords: STATCOM, Proportional-Double Derivative, RCGA-Optimization Technique, Power System Stability, SMIB Power System.
Słowa kluczowe: STATCOM, regulator proporcjonalno-podwójnie-różniczkujący, optymalizacja RCGA, SMIB.

1. Introduction

One of the main concerns in electric power system operation is repression of electromechanical oscillations. If sufficient damping is not available, while a disturbance occurs in power system, the oscillations can be increased and continued for minutes to cause loss of synchronism [1]. The lack of sufficient system damping is the major reason of the continuity and growth of oscillation in power system [2-4]. Recent advances in the field of Power Electronics provided an appropriate bed in order to using of Flexible AC Transmission System (FACTS) devices in power system. FACTS devices have high ability to preserve the synchronism of generators under all kind of disturbances [5, 6]. Although the initial target of shunt FACTS devices is to support bus voltage by injecting (or absorbing) reactive power, furthermore they are able to enhance the transient stability and damping of a power system [7]. When the machine angle increases (decreases), the shunt FACTS devices by operating in capacitive (inductive) mode can improve the transient stability of power system by increasing (decreasing) the power transfer capability. STATCOM is one of prominent member of FACTS family which is connected in parallel with transmission line. The STATCOM is characterized by a solid state synchronous voltage source convertor (VSC), which produces a balanced set of three sinusoidal voltages at the fundamental frequency with rapidly controllable amplitude and phase angle [8]. The efficiency of this device in increase transmission capacity, damping of low frequency oscillations, improve transient stability and controlling the terminal voltage has been confirmed in [3, 9-13]. From the viewpoint of power system dynamic stability, it is essential for STATCOM to equip with a supplementary damping controller in order to mitigate the power system oscillations. A number of different classical controllers such as Lead–Lag (LL), Proportional–Integral (PI), and Proportional–Integral–Derivative (PID) have been employed in FACTS devices as supplementary damping controller [14-18]. The main target of this paper is presentation of a novel Proportional-Double Derivative (PDD) controller for STATCOM in order to promote all scale of transient stability improvement, including: fewer undershoot, fewer overshoot and fewer settling time.

A variety of conventional design techniques have been applied for tuning controller parameters. The most common methods are based on the pole placement method [19, 20], eigenvalues sensitivities [21, 22], residue compensation [23], and also the current control theory. Unfortunately, the conventional methods are time consuming as they are repetitive and need heavy computation burden and slow convergence. In addition, process is sensitive to be trapped in local minima and the obtained response may not be optimal [11].

The progressive methods develop a technique to search for the optimum solutions via some sort of directed random search processes [24]. A suitable trait of the evolutionary methods is that they search for solutions without prior problem perception.

In recent years, a number of various ingenious computation techniques namely: Simulated Annealing (SA) algorithm, Evolutionary Programming (EP), Genetic Algorithm (GA), Differential Evolution (DE) and Particle Swarm Optimization (PSO) have been employed by scholars to solve the different optimization problems of electrical engineering. The high performance of GA technique to solve the non-linear objectives has been approved in many literatures. In this work, RCGA optimization technique is selected to solve the optimization problem and optimum tune the parameters of these classical controllers in order to enhance the power system stability.

For proving the robustness of PDD damping controller, it has been compared with PI, LL and PID controllers. Furthermore, dynamic performance of these controllers is analyzed and appraised under three different conditions of disturbance in SMIB power system.

Eventually, non-linear time-domain simulation results reveal that the STATCOM-based PDD damping controller provides robust dynamic performance as compared with other classical controllers.

2. Description of the Implemented Real Coded Genetic Algorithm Technique

Genetic Algorithm is a kind of random search optimization technique based on the mechanism of natural evolution and the survival of the best chromosome. A genetic algorithm is founded by a cycle of three stages, namely: assessment of each chromosome, selection of chromosome, creation of a new population.

GA maintains and controls a population of solutions and enhances performance of fitness function in their search for better solutions. Reproducing the generation and keeping the best individuals for next generation, the best gens will be obtained. The RCGA optimization process can be described as below:

2.1. Initialization

To commence the RCGA optimization process, initial population shall be specified. An initial population can randomly be generated or obtain from other methods [24]. The length limitation of variables should determine for optimization problem.

$$p=(p_{hi}-p_{lo})p_{norm}+p_{lo} \quad (1)$$

2.2. Objective Function

Each individual represents a possible solution to optimize the fitness function. The fitness for each individual in the population is evaluated by taking objective function. Eliminating the worst individuals, a new population is created, while the most highly fit members in a population are selected to pass information to the next generation.

$$chromosome\,(variables)=[P_1,P_2,...,P_{N\,var}] \quad (2)$$

$$cos\,t=f(chromoso\,me)=f(P_1,P_2,...,P_{N\,var}) \quad (3)$$

2.3. Selection Function

The selection function attempts to implement pressure on the population like natural biological systems. The selection function decides which of the individuals can survive and transfer genetic characteristic to the next generation. The selection function specifies which individuals are selected for crossover. Several methods exist that parents are chosen according to efficiency of their fitness. In this work, roulette wheel selection method is considered and is described in details in [25].

2.4. Genetic Operator

There are two main operators in GA optimization process which are basic search mechanism of the GA techniques: crossover and mutation. They are used to create new population based on acquirement the best solution.

2.4.1. Crossover

Crossover is the core of genetic operation, which helps to achieve the new regions in the search space. Conceptually, pairs of individuals are chosen randomly from the population and fit of each pair is allowed to mate. Thus, parameter where crossover occurs expressed as:

$$\alpha=roundup\{random * N_{var}\} \quad (4)$$

Each pair of mates creates a child bearing some mix of the two parents.

$$parent\,1=[p_{m1}p_{m2}\cdots p_{m\alpha}\cdots p_{mN\,var}] \quad (5)$$

$$parent\,2=[p_{d1}p_{d2}\cdots p_{d\alpha}\cdots p_{dN\,var}] \quad (6)$$

Then the selected variables are combined to form new variables that will appear in the children:

$$p_{new\,1}=p_{m\alpha}-\beta\,[p_{m\alpha}-p_{d\alpha}] \quad (7)$$

$$p_{new\,2}=p_{d\alpha}+\beta\,[p_{m\alpha}-p_{d\alpha}] \quad (8)$$

Where, β is also a random value between 0 and 1. The final step is to complete the crossover with the rest of the chromosome as before:

$$offspring\_1=[\,p_{m1}p_{m2}\cdots p_{new1}\cdots p_{dN\,var}\,] \quad (9)$$

$$ofspring\_2=[\,p_{d1}p_{d2}\cdots p_{new2}\cdots p_{mN\,var}\,] \quad (10)$$

2.4.2. Mutation

The mutation process is used to avoid missing significant information at a special situation in the decisions. Mutation is usually considered as an auxiliary operator to extend the search space and cause release from a local optimum when used cautiously with the selection and crossover systems. With added a normally distributed random number to the variable, uniform mutation will be obtained:

$$p_n^{'}=p_n+\sigma\,N_n\,(0,1) \quad (11)$$

2.5. Stopping Criterion

The stopping scale can be considered as: the maximum number of generation, population convergence criteria, lack of improvement in the best solution over a specified number of generations or target value for the objective function. With ending of generation the best individuals will be obtained.

3. Single Machine, Infinite Bus Power System

The SMIB power system has been simulated in MATLAB/SIMULINK environment. A simple model of suggested power system without presence of STATCOM is shown in Fig 1. Also, equivalent circuit of the power system is exhibited in Fig 2. It is almost similar to the power system used in [4].

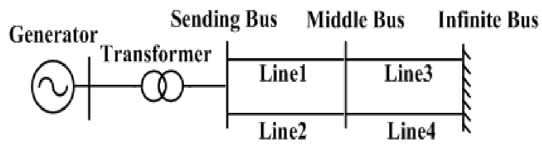

Fig. 1. Single line diagram of SMIB system

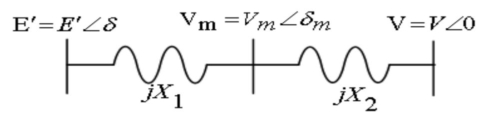

Fig. 2. Equivalent circuit of SMIB system

3.1. Mathematical Model

Considering a single line diagram of Fig. 2, the dynamics of the machine in classical model and electrical output power (P_e) of the machine can be represented by the following differential equations [26]:

$$\frac{d\delta}{dt}=\omega \quad (12)$$

$$\frac{d\omega}{dt}=\frac{1}{M}\left(P_m-P_e-D\omega\right) \quad (13)$$

$$Pe=P_{max}\,sin\,\delta \quad (14)$$

$$P\,max=\frac{E'V}{X_1+X_2} \quad (15)$$

3.2. Modeling of STATCOM

The STATCOM is characterized by a solid state synchronous voltage source convertor (VSC), which is capable of injecting controllable reactive current into the system. Consider that a STATCOM is placed at bus m in the SMIB system as presented in Fig. 3. A STATCOM can be represented by a shunt current source as shown in Fig. 4 [5].

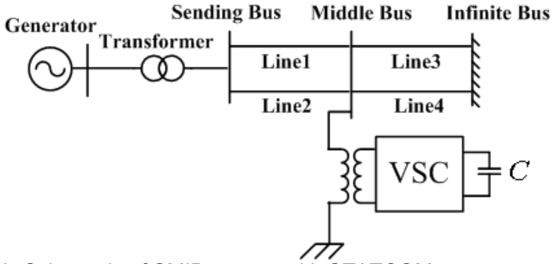

Fig. 3. Schematic of SMIB system with STATCOM

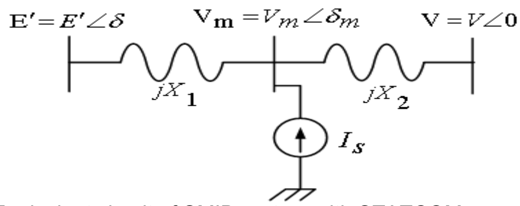

Fig. 4. Equivalent circuit of SMIB system with STATCOM

The STATCOM current can be expressed by following equation [5, 27]:

(16) $$I_S = I_S e^{j(\delta_m \pm \pi/2)}$$

The voltage of bus m can be written as:

(17) $$V_m = \left[(X_2 E' \cos\delta + X_1 V) + j(X_2 E' \sin\delta) \right] / (X_1 + X_2)$$

The voltage angle of bus m can be extracted from Equation (17):

(18) $$\tan(\delta_m) = \left(Im(V_m) \right) \Big/ \left(Re(V_m) \right)$$

(19) $$\delta_m = \tan^{-1}\left[\frac{X_2 E' \sin\delta}{X_2 E' \cos\delta + X_1 V} \right]$$

Ultimately, the electrical output power P_e of the machine with presence of STACOM can be written as [28]:

(20) $$Pe = P_{max} \sin\delta + f(\delta) I_S$$

where

(21) $$f(\delta) = \frac{X_2 E'}{X_1 + X_2} \sin(\delta - \delta_m)$$

So that, $f(\delta)$ is positive when δ oscillates in between zero and π. According to Equation (20), P_e can be modulated by controlling the shunt reactive current I_S.

3.3. Supplementary Damping Controllers

The risk of possible instability following a disturbance is one of the consequences of such a stressed system. Although the performance of STATCOM to enhance power system stability has been well approved but to more damp power system oscillations, it is necessary for STATCOM to equip with a supplementary damping controller. In this paper, a novel PDD structure is introduced for STATCOM, which is expressed by following equation:

(22) $$Is = \left(K_p + K_{dd} * S^2 \right) * \omega$$

The following equations depict the relationship between PI, PID and LL controllers with I_S, which are presented by Equation (23), (24), and (25).

(23) $$Is = \left(K_p + K_i / S \right) * \omega$$

(24) $$Is = \left(K_p + K_i / S + K_d * S \right) * \omega$$

(25) $$Is = \left(K_p \frac{1 + TS}{1 + 0.2S} \right) * \omega$$

The simulation model for dynamic analysis of power system with presence of STATCOM is presented in Fig. 5.

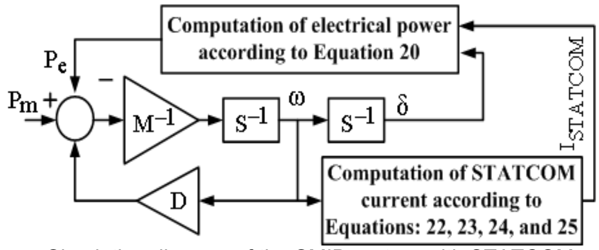

Fig. 5. Simulation diagram of the SMIB system with STATCOM

3.4. Optimum Tune the Parameters of Proposed PDD Controller and Classical Controllers

In this work, RCGA optimization technique is applied to solve the optimization problem and to evaluate the robustness of proposed PDD damping controller in order to damp the power system oscillations. To enhance the system stability and damping performance of these classical controllers, the total fitness function is determined as Equation (27) [29]:

(26) $$J = \int_{t=0}^{t=t_{sim}} |\Delta\omega| . t . dt$$

(27) $$F = \sum_{i=1}^{N_p} J_i$$

The time-domain simulation of the non-linear system model is performed for the simulation period. It is aimed to minimize this fitness function in order to improve the system response in terms of the settling time, overshoots and undershoot. The problem constraints are the optimized parameter bounds. Therefore, the design problem of STATCOM-based damping controllers is formulated as the following optimization problem:

(28) $$Minimize\ F$$

Subject to:

(29)

$$K_P^{min} \le K_P \le K_P^{max}, \quad K_{dd}^{min} \le K_{dd} \le K_{dd}^{max} \qquad \text{for PDD cot roller}$$

$$K_P^{min} \le K_P \le K_P^{max}, \quad K_i^{min} \le K_i \le K_i^{max}, \quad K_d^{min} \le K_d \le K_d^{max} \qquad \text{for PID controller}$$

$$K_P^{min} \le K_P \le K_P^{max}, \quad K_i^{min} \le K_i \le K_i^{max} \qquad \text{for PI controller}$$

$$K_P^{min} \le K_P \le K_P^{max} \qquad \text{for LL controller}$$

$$T^{min} \le T \le T^{max}$$

RCGA-optimization technique is employed to solve the optimization problem and optimal tuning of STATCOM-based damping controllers. The flowchart of the optimization based on optimum tune parameters of these damping controllers is described in Fig. 6.

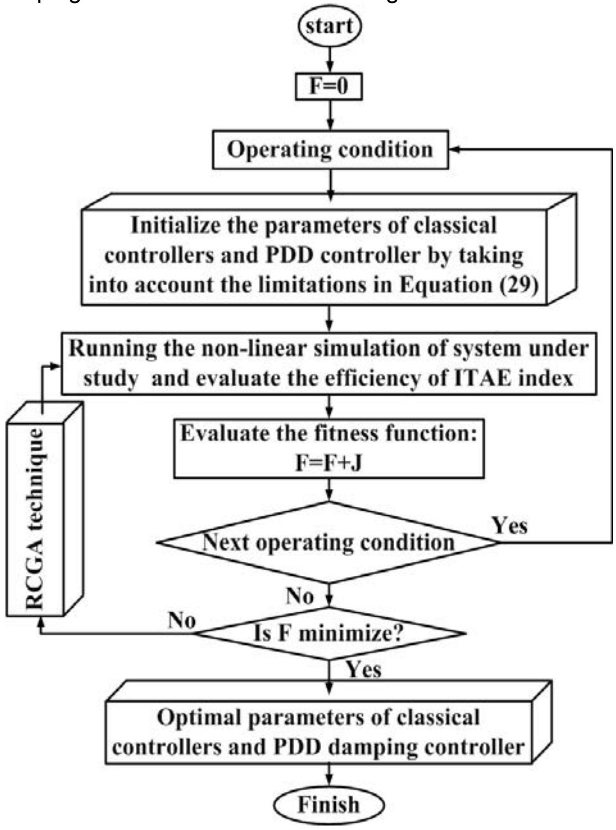

Fig.6. Flowchart of the optimization technique based on optimum tune parameters of STATCOM-based damping controllers

4. Simulation Results add Discussions

To assess the dynamic performance of proposed PDD damping controller and other damping controllers, three different conditions of disturbance are considered which are described in following states. In all three conditions, system status is nominal loading condition ($P=0.7^{p.u.}$).

The optimization of parameters of proposed PDD damping controller and other damping controllers is performed by evaluating the objective function as given in Equation (27), which considers three different conditions of disturbances. The optimal parameters of proposed PDD damping controller and other damping controllers are presented in Table 1.

Table 1: Optimal parameter of the damping controllers

PDD controller	K_p	K_{dd}	
	0.49843	0.00039	
PID controller	K_p	K_i	K_d
	0.49520	0.00536	0.00027
PI controller	K_p	K_i	
	0.49262	0.00255	
LL controller	K_p	T	
	0.49914	0.37292	

The following section results confirm the robustness of PDD damping controller than other damping controllers.

4.1. Three Phase Short Circuit

A 3-phase fault occurs in the infinite bus at t = 1s, then it is cleared after 0.25s. While, does not happen any disturbance in power system. As described above, RCGA optimization technique is employed to optimum tune the parameters of damping controllers in order to enhance power system stability and approve the dynamic performance of STATCOM-based PDD damping controller. The system response under 3-phase short circuit is exhibited in Fig. 7. These figure confirm that the proposed PDD damping controller is robust than other damping controllers in mitigation of power system oscillations.

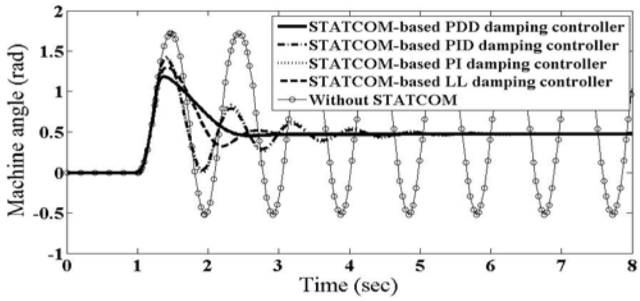

Fig. 7. Machine angle response under 3-ph fault

4.2. Impulse disturbance in Mechanical Power

To evaluate the dynamic performance of proposed PDD damping controller and its sufficiency, an impulse signal is occurred in mechanical power input at t=1s (without any disturbances occurrence in power system). The magnitude and duration impulse signal are 20^{pu} and 10ms, respectively. System response under this disturbance is displayed in Fig. 8. It is revealed that STATCOM-based PDD damping controller is offering the best dynamic performance in damping of power system oscillations.

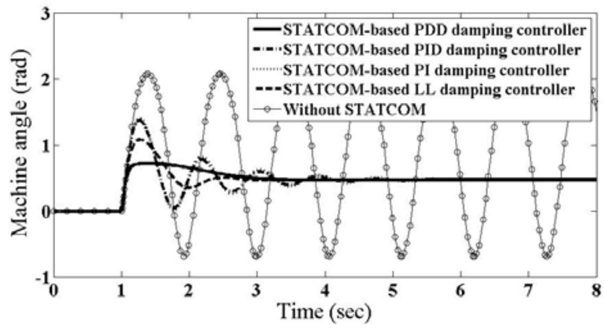

Fig. 8. Machine angle response under impulse disturbance in mechanical power input.

4.3. Change in Mechanical Power

For this state, a step change of 0.3 $^{p.u.}$ is considered on at t=1s, which is lasted for 5 sec. System response under change in mechanical power input is shown in Fig. 9. As discussed before, the power system stability is further improved in the presence of STATCOM-based PDD damping controller.

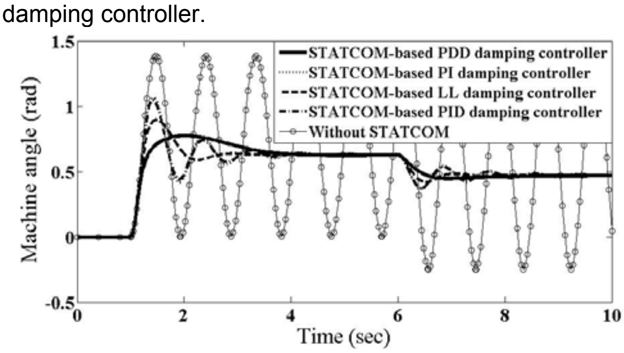

Fig. 9. Machine angle response under step change in mechanical power input.

5. Conclusion

In this paper, a novel robust Proportional-Double Derivative (PDD) structure is proposed as a supplementary controller for static synchronous compensator (STATCOM) to mitigate the power system oscillations. To approve the dynamic performance of proposed PDD damping controller, it has been deeply compared with Lead-Lag (LL), Proportional-Integral (PI), and Proportional-Integral-Derivative (PID) controllers. Dynamic performance of these controllers is also evaluated under three different conditions of disturbance in Single-Machine Infinite-Bus (SMIB) power system. The Real Coded Genetic Algorithm (RCGA) optimization technique due to have high sufficiency to solve the very non-linear objective is employed to optimally tune the parameters of these controllers in order to damp the power system oscillations. The obtained results of the power system stability improvement have shown that the STATCOM-based PDD damping controller is more robust and effective than others.

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