A Complementary SVC-based Damping Controller Design Using Multi-objective Evolutionary Algorithm

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Abstract—Static Var compensator (SVC) is one of flexible AC transmission system (FACTS) elements mainly used for reactive power and voltage control in power systems. This paper deals with multi-modal electromechanical oscillations damping in the presence of severe disturbances. These oscillations include local modes, inter-area modes and inter-plant modes. To enhance the damping of the oscillations, a complementary controller is added to voltage regulator of SVC. In order to design such a controller, a multi-objective optimization model is employed and non-dominated sorting genetic algorithm-II (NSGA-II) approach is used to produce sets of Pareto optimal solutions. Also, a fuzzy method is utilized to select the best compromise solution. The proposed method is examined on a two-area power system and simulation results illustrate the robustness and the efficiency of the proposed controller.

Keywords—Fuzzy method, Non-dominated sorting genetic algorithm (NSGA), Multi-objective optimization problem (MOOP), Pareto-optimal solutions, Damping Controller, Static Var compensator (SVC).

I. INTRODUCTION

When a power system is interconnected by weak transmission lines, low frequency electromechanical oscillations are observed. If damping of the oscillations is not enough, they are reinforced and may lead to instability of the system. Usually, electromechanical oscillations are divided into three categories, namely: local modes, inter-area-modes and inter-plant modes [1]. PSSs have been used for many years to add damping to local modes; but PSS does not have the same damping effect on the other oscillation modes [2]. Besides, PSS suffers from being liable in the event of great variations in voltage magnitude and may even results in leading power factor and losing system stability under severe disturbances, especially in the case of three phase faults at generator terminals [3].

In recent years, fast progresses in the field of power electronics have opened new opportunities for the application of the flexible alternating current transmission system (FACTS) devices as one of the most effective ways to improve both power system controllability and power transfer limits. Extremely fast control action of FACTS devices, makes them suitable for utilization in reactive power control. FACTS devices are divided into two main groups in according to the shunt or series connection to transmission system [4]. Series FACTS devices improve power oscillations stability [5], but do not have the same effectiveness of shunt FACTS devices to improve voltage profile of the system. Shunt FACTS controllers are used in transmission network to provide dynamic voltage control and to improve power flow control.

Static Var compensator (SVC) is one of the main shunt FACTS devices. The main role of SVC is to control voltage at the point of connection, and hence to maintain bus voltage approximately near to a constant level. In addition to voltage control, SVC could be employed for damping of electromechanical oscillations. In [6] a simple damping controller has been proposed for SVC, however, the controller was designed using linear model of power system and hence may not be dependable in the case of severe disturbances due to the nonlinear nature of the system. Thus, the ability of SVC to improve power oscillations damping has not been investigated accurately. Hence, this paper focuses to deal with this problem.

SVC with only its terminal voltage as input control signal cannot participate in power system oscillations damping effectively. Therefore, a complementary power system
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damping controller (CPSDC) is required to make the SVC suitable for damping of oscillations [7]. In [6] by using residue analysis method that was proposed in [8] and [9], a proper input signal was adopted for this controller. It is noteworthy that the selected signal consists of comprehensive information about different regions of power system, then containing the high controllability and observability [1], [6]. After choosing the input signal, design process of the controller is commenced. As mentioned earlier, three types of oscillation modes are available and damping them together is the aim of the controller proposed in this paper. Thus, the problem is a multi-objective optimization problem (MOOP). The procedure of design is through solving this MOOP. It is difficult to design a controller capable of damping all oscillating modes, simultaneously. To overcome the above problem, this paper employs Pareto search via non-dominated sorting genetic algorithm-II (NSGA-II) method [10]. In fact, NSGA-II approach is used to design a SVC-based controller to improve transient performance of power systems by damping all the three oscillating modes simultaneously. It is noteworthy that the attractive feature of MOOP algorithms, e.g. NSGA-II, is their ability to find a wide range of non-dominated solutions close to true Pareto-optimal solutions [11].

The rest of the paper is organized as follows. The structure of SVC-based CPSDC is introduced in Section 2. Afterwards, the problem formulation and the objectives of this study to be optimized are presented in Section 3. Then, NSGA-II approach for MOOP is given in Section 4. Case study and simulation results are presented in Section 5. Finally, the paper is concluded in Section 6.

II. STRUCTURE OF THE SVC-BASED CPSDC

Since the SVCs are employed primarily for voltage control, their contribution to damping of system oscillations is usually low. This is the reason why the CPSDC is required to assist for damping of power system oscillations.

Structure of the CPSDC for a SVC is shown in Fig. 1. The speed difference of generators (i.e. \( \Delta \omega_r \)) which is a wide area signal [6] serves as the input signal, and auxiliary voltage (i.e. \( V_c \)) is the output of the controller. It is observed from Fig. 1 that the output signal is fed to regulator of SVC. By this way, the value of SVC’s susceptance (\( B_{SVC} \)) is changed according to the control law. Afterwards, the SVC injects a suitable reactive current to its connected bus.

Fig. 1. Block diagram of SVC-based CPSDC

The block diagram of a SVC-based CPSDC includes a gain block (\( K_{STAB} \)), a washout block, and two lead-lag compensator blocks. Washout function serves as a high-pass filter, with the time constant \( T_W \) that is high enough to allow electromechanical oscillations to pass unchanged. From the viewpoint of the washout, the value of \( T_W \) is not critical and may be in the range of 1 second up to 20 seconds [1]. As shown in Fig. 1, the parameters of phase compensator block diagrams (time constants \( T_1 \), \( T_2 \), \( T_3 \) and \( T_4 \)) provide the appropriate phase-lead characteristics to compensate the phase lag between the input and the output signals.

In the proposed structure for the CPSDC, the washout time constant (\( T_W \)) and the parameters of denominator in lead-lag block diagrams are usually pre-determined, e.g. \( T_2 = T_4 = 0.3 \) seconds and \( T_W = 10 \) seconds [18]. Parameters of numerator in lead-lag block diagram (\( T_1 \) and \( T_3 \)) and the gain of stabilizer (\( K_{STAB} \)), should be calculated through the optimization procedure, which is presented in sections 3 and 4.

III. OPTIMIZATION OBJECTIVES AND PROBLEM FORMULATION

Generally, there are three important oscillating modes which may appear in multi-machines power systems due to occurrence of disturbances. As mentioned previously, these modes are as follows: Local modes, inter-area modes and inter-plant modes. Participation of a local mode in angular speed of the corresponding generator is high, and then the mode could be damped by minimizing speed deviations of that generator. Inter-area modes are appeared in speed difference between generators of two interconnected areas. Inter-plant modes are emerged in power flow of tie-lines [5]. This paper focuses on designing the CPSDC in order to minimize the above oscillation modes as objectives. Thus, the problem can be formulated as a MOOP as follows.

\[
f = \min(f_1, f_2, f_3)
\]  

where [5]:

\[
f_1 = \int_{t=0}^{t_0} |\Delta \omega_r| dt
\]

\[
f_2 = \int_{t=0}^{t_0} |\Delta \omega_l| dt
\]

\[
f_3 = \int_{t=0}^{t_0} |\Delta P_L| dt
\]

where (1) is the multi-objective function, (2), (3) and (4) are the local mode, inter-area mode and inter-plant modes deviations, respectively.
IV. MOOP USING NSGA-II APPROACH AND FUZZY SELECTING TECHNIQUE

Some MOOP algorithms are based on pre-fixing a weight vector. As the name suggests, each objective function is multiplied by a weight to find the corresponding Pareto-optimal solution. The most widely used methods based on this procedure for generating such non-inferior solutions are: weighted-based genetic algorithm (WBGA), ε-constraint method and weighed min–max method. These weighted-sum approaches just find one Pareto-optimal solution corresponding to a particular set of weights. Besides, these methods do not preserve good diversity [11]. Later, with appearance of new methods, these deficiencies were eliminated by introducing the non-domination concept and an explicit diversity-preserving operator [11]. The new approaches include multi-objective genetic algorithm (MOGAs) [12], Niched-Pareto genetic algorithm (NPGAs) [13], strength Pareto evolutionary algorithm (SPEA) [14], and non-sorting genetic algorithm (NSGAs) [15]. All these methods are followed from theory of David E. Goldberg [11] and have found well-converged and well-distributed sets of trade-off solutions in test problems as well as real-world problems.

Up here, all of the presented multi-objective evolutionary algorithms (MOEAs) do not use any elite-preserving operator. As the name suggests, an elite-preserving operator uses the elite concept of population by giving them the opportunity to be directly carried over the next generation. A number of important elitist multi-objective algorithms are NSGA-II [10], SPEA2 [16] and MOMGA-II [17]. In this paper, NSGA-II method is applied to obtain Pareto-optimal solutions. Generally, MOOP algorithms use non-dominance definition and satisfy the following two aims which are in conflict with each other [10].

- Finding a set of optimal Pareto solutions or close to them.
- Achieving best diversity among non-dominated solutions.

The authors in [10] have proposed an improved version of the NSGA, i.e. NSGA-II. This approach, in most problems, is able to find better spread of solutions and better convergence to the true Pareto-optimal front in comparison with other elitist MOEAs, namely Pareto-archived evolution strategy and SPEAs [11]. With assuming a minimization problem, following definitions has been described to explain NSGA-II method [10].

Definition 1. (Pareto Dominance): a vector $u = (u_1, u_2, \ldots, u_n)$ is said to dominate another vector $v = (v_1, v_2, \ldots, v_n)$ (denoted by $u \prec v$) if and only if $u$ is partially less than $v$, i.e.:

\[
\forall i \in \{1, \ldots, k\}, u_i \leq v_i \land \exists i \in \{1, \ldots, k\} : u_i < v_i.
\]

Definition 2. (Pareto-optimal solution): A solution $x_{i} \in U$ is said to be Pareto-optimal if and only if there is no $x_{j} \in V$ for which $V = f(x_{i}) = (V_1, \ldots, V_n)$ dominates $U = f(x_{j}) = (u_1, \ldots, u_n)$.

Now, NSGA-II algorithm is as follows:

Initialization: in the first stage of genetic algorithm, individuals of initial population are generated at random or through the use of specified information.

Evaluation of population: the performance of each individual is evaluated in this stage. In this paper to investigate the performance of each individual, the mentioned three objective functions are evaluated. These values define the fitness of each individual which shows their merit to be selected.

Genetic Operations: by using these operators, GA generates the new and improved population. These operations are selection, crossover and mutation. Selection operator in NSGA-II acts based on non-dominated sorting of population and crowded-comparison operator in descending order.

To demonstrate the proposed selection operator, the t-th generation of algorithm is described. Parent population ($P_t$) and offspring population ($Q_t$) are combined to form $R_t = P_t \cup Q_t$ with size of 2N, if the population size is assumed to be N. Then, population $R_t$ is sorted based on non-dominance concept. Since all previous and current population members are included in $R_t$, elitism is insured. Now, solutions belonging to the best non-dominated set, $F_t$, are the best solutions in the combined population and must be emphasized more than any other solution. If the size of $F_t$ is smaller than N, we definitely choose all members of $F_t$ for the new population $P_{t+1}$. Remaining members of $P_{t+1}$ are chosen from subsequent non-dominated fronts in the order of their ranking. Thus, solutions from the set $F_2$ are chosen next, followed by solutions from the set $F_3$, and so on. This procedure is continued until no more sets can be accommodated. Assume that the set $F_k$ is the last non-dominated set beyond which no other set can be accommodated. Generally, the count of solutions in all set from $F_1$ to $F_k$ would be larger than the population size. To choose exactly N population members, in addition to non-dominated sorting, the solutions of the last front $F_k$ are sorted based on crowded-comparison operator in descending order. It helps to choose the best solutions needed to fill all population slots which have appropriate crowding. The new population $P_{t+1}$ of size N is now used for selection, crossover, and mutation to create new population $Q_{t+1}$ of size N. It is important to note that we use a binary tournament selection operator but the selection criterion is now based on the crowded-comparison operator. Since this operator requires both the rank and crowded distance of each solution in the population, so these quantities are calculated while forming the population. The process of generating new population by crowded-comparison operator is shown in Fig.2 [10].

Termination condition: if the number of generation is less than the maximum number of generation, the algorithm is back to step 2 to continue, otherwise the algorithm is terminated.

If the algorithm is ended, the specified numbers of Pareto-optimal set are chosen as optimal solutions.

The necessary information of NSGA-II method is given in Table 1.
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Non-dominated sorting

Crowding distance sorting

Rejected

Fig. 2. Schematic view of NSGA-II [10]

V. CASE STUDY AND SIMULATION RESULTS

To examine the proposed complementary damping controller, a multi-machine power system is adopted here. Figure 3 depicts the single-line diagram of the system. The system consists of four synchronous generators and two areas and an SVC is located at Bus 8. The detailed dynamic data of the system are extracted from [1].

In this paper speed difference between generators G1 and G3 is considered as the input signal of the SVC. Each individual of population includes parameters of the SVC-based CPSDC, so the fitness of each individual is calculated by simulating the dynamic behavior of the system.

As it is evident from Fig. 3, the areas are connected via double circuit transmission line (tie-line). When the multi-machine system is subjected to severe disturbances, power flowing through the tie-line experiences severe electromechanical oscillations. Thus, the SVC enhances performance of the system by employing the proposed CPSDC. In this circumstance, the SVC must inject or absorb appropriate reactive power to damp oscillations in addition to voltage improvement.

A. Applying the optimization algorithm to generate Pareto-optimal set

The Pareto-optimal set can be extremely large or even contain an infinite number of solutions. However, it is not reasonable to specify entire Pareto-optimal set, because it is so enormous and time consuming computationally. Therefore, a practical approach to solve MOOPs is to investigate a set of solutions that represent the Pareto-optimal set as much as possible. Hence, after the generation is complete and algorithm is terminated, the limited number of solutions according to low order ranking and high crowding is selected. Thus, in this paper 10 numbers of Pareto solutions are exhibited.

Upon having the Pareto-optimal set, decision maker can select the best optimal solution according to the objective which has the most importance. Due to the imprecise nature of the decision maker’s judgment, a fuzzy method is applied here to select the best compromise solution among obtained Pareto-optimal set. The j-th objective function of the i-th solution in the Pareto-optimal set, \( f_{R}^{i} \), is represented by a membership function \( \mu_{ij} \) which is defined as follows [19]:

\[
\mu_{ij} = W_j \times \begin{cases} 
1 & f_{j}^{\max} > f_{j}^{i} \\
\frac{f_{j}^{\max} - f_{j}^{i}}{f_{j}^{\max} - f_{j}^{\min}} & f_{j}^{\min} < f_{j}^{i} < f_{j}^{\max} \\
0 & f_{j}^{i} > f_{j}^{\max}
\end{cases}
\] (5)

where \( f_{j}^{\max} \) and \( f_{j}^{\min} \) are the maximum and minimum value of the j-th objective function. It is worth mentioning that all Pareto-optimal solutions with respect to all objectives are the best solutions, because these solutions are resulted from the seeking of entire search-space by NSGA-II method. However, there are objective preferences in the selecting of final optimal solution between all obtained non-dominated solutions. Then, a weighting factor, \( W_j \), is considered for the j-th objective function.

If a tie-line power oscillation is damped slowly, it may cause to outage of the tie-line and consequently, the network will be islanded, which is not desirable. Thus, it is necessary to damp the tie-line power oscillations efficiently. As a result, the objective of damping the inter-plant mode is more important. Therefore, the weighted coefficients of membership function corresponding to the objective functions (\( f_1, f_2 \) and \( f_3 \)) are assumed as follows: \( W_1=0.6, W_2=0.2 \) and \( W_3=0.2 \).
Also, for i-th non-dominated solution, the normalized membership function, $\zeta_i$, is calculated as follows:

$$\zeta_i = \frac{\sum_{j=1}^{n} \mu_j}{\sum_{j=1}^{m} \sum_{i=1}^{n} \mu_j}$$  \hspace{1cm} (1)

Where $n$ is the number of objective functions, $m$ is the number of non-dominated solutions. The best compromise solution is one having maximum value of $\zeta_i$.

To obtain the Pareto-optimal solutions, time-domain simulation is needed. Hence a three phase 3-cycles fault is applied on the tie-line between the Bus 8 and Bus 9, near the Bus 9. The fault occurs at $t=1$ second and cleared after 3-cycle without outage of the line. Then (2)-(4) are calculated numerically for any individual in each generation. Then, using the above obtained values for $f_j$ ($j=1, 2, 3$), the NSGA-II approach produces the next generation and corresponding control parameters for any individual. Pseudo code of the method is as follows:

**For generation = 1 to $G_{max}$**

- **For Individual = 1 to $I_{max}$**
  - Perform time-domain simulation and calculate (2)-(4) for any individual.
  - End
- Run NSGA-II algorithm to obtain the next generation.

In this paper the values of $G_{max}$ and $I_{max}$ are set to 6 and 20, respectively. Pareto-optimal solutions, the parameters of the proposed CPSDC, objective functions values along with the membership function for each solution are given in table 2.

It is evident from table 2 that, solution Sol-1 has maximum membership function value. Hence, Sol-1 is selected as the best compromise solution and the CPSDC is tuned based on the corresponding parameters, i.e. $K_{STAB}=50.954$, $T_1=0.2137$ second and $T_3=0.154$ seconds.

**B. Simulation results**

To examine both robustness and effectiveness of the proposed controller, several events are simulated and the system dynamic behavior with and without the controller is analyzed. The following cases are studied:

- **Case 1: Symmetrical three phase fault**
- **Case 2: Transmission line outage**
- **Case 3: Change in the system load**

1) **Case 1: Symmetrical three phase fault**

In this case the same three phase fault, in which the controller was designed based on it, is applied to the system. The power flow deviation of the tie-line is depicted in Fig. 4-(a). It is observed that a considerable improvement in oscillations achieved in the case of applying the proposed CPSDC. The speed difference of generators G1 and G2 shows local modes, while the speed difference of generators G1 and G3 exhibits inter-area modes. Thus, Figure 4-(b) and Fig.4-(c) illustrate the local and inter-area oscillations, respectively. It is observed from these figures that the controller is so effective for damping of multi-modal oscillations. In the presence of the controller, its output is added as an auxiliary signal to the input of SVC voltage regulator. This leads to the susceptance tracks variation of speed difference of generators. It is easy to explain how the susceptance is varied. In fact, in the earlier moments of the fault, susceptance has large variations similar the speed difference of generators. But, in the next times its variations become smaller. Besides, it is clearly shown in Fig.4-(d) that susceptance of the SVC with the controller has reasonable variations in comparison with the state that no auxiliary controller exists.
Case 2: Transmission line outage

To show the robustness of the designed controller, another disturbance which the controller is not designed based on it, is applied to the system.

For this purpose, one of the transmission lines between Bus8 and Bus9 is tripped out at $t=1$ second for duration of 8-cycles. The tie-line (between Buses 5 and 9) power flow, speed difference between generators G1 and G3 along with the speed difference between generators G1 and G2 are depicted in Figs. 5(a)-(c), respectively. It is observed from these figures that the controller has the same best performance and still damps the oscillations effectively.

Case 3: Change in the system load

The efficiency of the proposed controller is also examined for small signal disturbances, thus load 1 in the Area1 (i.e. $P_{D1} + jQ_{D1}$ at Bus 5) has a step change at $t=1$ second and is increased 10% of its initial values. For this case, The tie-line (between Buses 5 and 9) power flow, speed deference between generators G1 and G3 along with the speed difference between generators G1 and G2 are depicted in Figs. 6(a)-(c), respectively. As it is evident from these figures, the proposed controller can also improve small signal stability of the system.
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Fig. 6. system response to load change in Area1 (Case-3). (a) Tie-line active power flow. (b) Speed difference between generators G1 and G3 (pu). (c) Speed difference between generators G1 and G2 (pu).

VI. CONCLUSION

In this paper, a complementary controller is proposed and added to SVC voltage regulator, in order to increase damping of power system electromechanical oscillations. The main goal of design is minimization of multi-modal oscillations include: local modes, inter-area modes and inter-plant modes. Damping of all aforementioned oscillation modes are considered as objective functions. Therefore, the design problem is multi-objective optimization problem, time-domain based and parameter constrained. To solve the problem, NSGA-II approach is employed to generate Pareto-optimal solutions that satisfy all conflicting objectives. Besides, a fuzzy method has been used to select the best compromise solution. It is observed that SVC with the proposed controller, can effectively participate in electromechanical oscillations damping and recovering equilibrium point of the system. The performance of the proposed controller is verified at the presence of various disturbances. Simulation results imply that the proposed controller is robust and efficient in improving dynamic behavior of power systems.

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