Optimized Allocation of STATCOMs based on Equivalent Impedance Modeling of VSCs Using Genetic algorithm

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Abstract **- Static synchronous Compensators (STATCOMs) as a flexible AC transmission system (FACTS) controller can improve the power system parameters if they have been optimally allocated. In this paper, a novel approach is introduced to optimize the placement of STATCOMs according to a new objective function including voltage profile of different system points (VP) and transmission capability indices. Using equivalent impedance modeling of voltage source converters (VSCs) and sensitivity analysis in order to calculate the required indices help improve the speed of calculations and the convergence rate of optimization problem solving. Genetic Algorithm (GA) is used to solve the optimization problem. The proposed method is applied on a test system. The test results can clarify the effectiveness of the proposed method.**

Index Terms - Static Synchronous Compensators (STATCOM), Optimized Placement, Genetic Algorithm (GA), Transmission Capability, Transient Stability

NOMENCLATURE

$\vec{I}_i$ Current of the parallel branch connected to bus *i*

$\vec{V}_i$ Voltage of bus *i*

Xt STATCOM transformers reactance

Ve_i Equivalent voltage of STATCOM

ϕ_i Phase of the voltage of bus *i*

Z_{ij}, Z_L Line impedance

X_{ij} Reactance of line connecting two buses *i* and *j*

Ze_i Equivalent impedance of STATCOM

$\overline{V}_{init}, \overline{V}_{new}$ Voltage matrix of initial (without any STATCOM) and compensated states

$\overline{\Delta V}$ Voltage variation matrix

ΔY Admittance variation matrix

Δy_{ij} *i*-th row and *j*-th column of ΔY

Y_{init}, Y_{new} Admittance matrix of initial and compensated states

$\vec{I}_{init}$, $\vec{I}_{new}$ Current matrix of initial and compensated states

$p_{j,\max}$ Maximum transmittable active power of line *j*

$p_{j,\max}^{init}, p_{j,\max}^{comp}$ Initial and compensated values of $p_{j,\max}$

VP_i Voltage profile of bus *i*

δ_j Phase angle of line *j*

ω_i Weight coefficient of bus *i* regarding to voltage profile index of objective function

ω_j' Weight coefficient of line *j* regarding to transmission capability index of objective function

ω_j'' Weight coefficient of bus *j* regarding to phase angle index of objective function

N Number of network buses

M Number of network lines

I. INTRODUCTION

In recent years, some researches recommend the using of Flexible AC Transmission systems (FACTS) to improve different system characteristics. One of the most important parameter of designing the FACTS devices is their allocation. Hence, different approaches have been introduced to optimize the placement of FACTS compensators. Also, various objective functions have been studied in some recent researches in order to determine the best location of FACTS controllers.

Static Synchronous Compensators (STATCOM) is one type of FACTS compensators connecting in parallel condition to power systems. STATCOMs supply reactive power and improve the voltage profile of different points [1-3].

STATCOMs and other similar FACTS controllers contain Voltage Source Converters (VSCs) can be operated for different purposes. Furthermore, it is interested for designers and operators to reach a perfect view of the effects of STATCOMs and other FACTS devices on power system, particularly in large scale studies.

Since it is necessary to solve enormous complicated equations in order to obtain a good solution of STATCOM allocation,

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selecting an approach which simplifies the calculations can be useful. The sensitivity analysis is one of the most applicable methods help reduce the required calculations of VSCs and FACTS devices [4-7]. In some references such as [5,6], the sensitivity analysis has been used to make a direct relation between control and observed variables when FACTS devices are installed. In addition to using of sensitivity analysis, indirect modeling of VSCS is recommended for optimization problems regarding to allocation of FACTS devices, because in this way, the power flow calculation in each optimization step and accurate modeling of VSCs are not necessary [8,9].

In this paper, a novel approach is proposed to find the optimum solution of STATCOMs allocation. In the proposed approach, using sensitivity analysis helps simplify the required calculations such as power flow equations and iterations.

Different objective functions such as voltage stability [10], transmission capability and other power flow characteristics [11,12], under operating of distributed generations (DGs) and renewable energy variations in demand and supply sides [13] are studied in order to find the best solution of FACTS allocation. In this paper, a novel objective function including voltage profile, transmission capability and stability is selected to optimize the allocation of STATCOMs. The introduced approach is based on sensitivity analysis and equivalent impedance model of VSCs which is similar to [9]. The introduced method is applied on a test system. Moreover, the optimization problem is solved by Genetic Algorithm (GA). The test results clarify the effectiveness of the proposed approach.

II. Equivalent Impedance Modeling of VSCs

In Fig. (1), a STATCOM schematic has been presented. The reactive power exchanged between system and STATCOM can be modeled by equivalent impedance (in parallel). It should be mentioned STATCOM does not have active power exchange with the network. Figs. (1-b) and (1-c) show the equivalent voltage-sourced and equivalent impedance schematic of a STATCOM connected to bus (i), respectively.

The relation of calculating the equivalent impedance of the STATCOM can be obtained as follows:

$$\vec{I}_i = \frac{\vec{Ve}_i - \vec{V}_i}{jXt_i} \tag{1}$$

$$Ze_i = \frac{\vec{Ve}_i}{\vec{I}_i} \tag{2}$$

By using the above equations, it is possible to calculate the admittance variation matrix shown in Eq. (3). Afterwards the modified voltage of buses can be obtained. The calculation of different parameters of introduced objective function is feasible based on voltage of buses.

$$\begin{bmatrix} \Delta Y_{ii} & \Delta Y_{ij} \\ \Delta Y_{ji} & \Delta Y_{jj} \end{bmatrix} = \begin{bmatrix} \dfrac{1}{Ze_i + jXt_i} & 0 \\ 0 & 0 \end{bmatrix} \tag{3}$$
$$\Delta Y_{pq} = 0 \;\; for \;\; p,q \neq i \;\; or \;\; j$$

To find the compensated voltage, the voltage variation matrix should be considered as follows:

$$\vec{V}_{new} = \vec{V}_{init} + \Delta\vec{V} \tag{4}$$

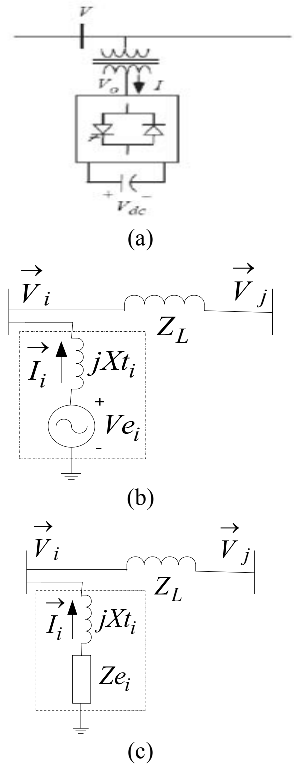

Fig. 1. STATCOM (a) schematic (b) equivalent voltage-sourced view (c) equivalent impedance model

Also, the current matrix can be calculated as Eq. (5):

$$\vec{I}_{new} = Y_{new}\vec{V}_{new} = \left(Y_{init} + \Delta Y\right)\left(\vec{V}_{init} + \Delta\vec{V}\right) \tag{5}$$

Expanding of Eq. (6) leads to:

$$\vec{I}_{new} = Y_{init}.\vec{V}_{init} + Y_{init}.\Delta\vec{V} + \Delta Y.\vec{V}_{init} + \Delta Y.\Delta\vec{V} \tag{6}$$

It assumes that the injected currents by compensators are negligible in comparison with main currents passing through system lines. Therefore, the compensated and initial current matrices ($\vec{I}_{new}$ and $\vec{I}_{init}$) can be assumed equal. Furthermore, the multiplying of voltage and admittance variations matrices is about zero.

$$\begin{cases} \vec{I}_{new} = \vec{I}_{init} + \vec{I}_{injected} \simeq \vec{I}_{init} = Y_{init}\vec{V}_{init} \\ \Delta Y.\Delta\vec{V} \simeq 0 \end{cases} \tag{7}$$

According above equations and explanations, Eq. (8) is obtained:

$$\Delta\vec{V} = -Y_{init}{}^{-1}.\Delta Y.\vec{V}_{init} \tag{8}$$

To obtain a reasonable value of $\Delta\vec{V}$, Eq. (8) should be solved with an iterative process.

The first step of calculations of equivalent model and sensitivity analysis is finding the load flow results of initial system state. Afterward, the admittance variations matrix (ΔY) should be calculated. Then, it is possible to find the voltage variations ($\Delta\vec{V}$). In the end of each iteration, voltage variations are compared with the previous ones. If voltage variations of buses are approximately constant, the algorithm will stop and the reasonable results have been obtained.

The advantage of the introduced method is that it determines a relation between admittance variations and voltage variations are caused by compensators.

III. Objective Function and Optimization Process

Different characteristics and indices have been selected in order to optimal allocate FACTS devices. Improvement of voltage profile of different points of a power system is one of the most important objects of using FACTS compensators. In addition to voltage profile, transmission capability is another index which affects the reliability and performance of system. Furthermore, phase angle (δ) is a prominent parameter affecting the transient stability. If δ decreases, the stability margin of transmission line will be improved [4,9]. In Eq. (9), three important system parameters such as voltage profile, transmission capability of lines and phase angle are demonstrated as follows:

$$\begin{cases} VP_i = |V_i - 1| & i = 1:N \\ P_{j,Max} = \dfrac{|V_s||V_r|}{X_j} & j = 1:M \\ \delta_j = |\phi_s - \varphi_r| & j = 1:M \end{cases} \tag{9}$$

In Eq. (9), VP_i is the difference of voltage magnitude of bus (*i*) and reference value (1 p.u). Also, $P_{ij,Max}$ is the maximum value of active power transmission capability of line connecting two buses (*i*) and (*j*). Moreover, δ_{ij} is the difference between voltage angles of two connected buses (*i*) and (*j*) which is called phase angle. In this paper, a novel objective function including three mentioned power system parameters is proposed. The proposed multi-objective function is presented in Eq. (10).

$$O.F = \sum_{i=1}^{N} \omega_i \left(\frac{VP_i^{comp} - VP_i^{init}}{VP_{init}}\right) + \dots$$
$$\dots \sum_{j=1}^{M} \left[\omega_j{}' \left(\frac{p_{j,\max}^{init} - p_{j,\max}^{comp}}{p_{\max}^{init}}\right) + \omega_j{}'' \left(\frac{\delta_j^{comp} - \delta_j^{init}}{\delta^{init}}\right)\right] \tag{10}$$

The different indices of proposed objective function with proper weighting coefficients create an appropriate criterion to allocate the STATCOMs. The weight coefficients determine the relative importance between voltage profile, transmission capability, and phase angle while a reasonable relation between them is made.

To solve the optimization problem based on objective function shown in Eq. (10), using an intelligent optimization algorithm is necessary. Genetic Algorithm (GA) is selected to solve the optimization problem of this paper. The MATLAB optimization toolbox is used and GA is implemented on MATLAB software. The optimum solution which is obtained from solving the optimization problem determines the placement of STATCOMs and the magnitude of VSCs of each compensator.

IV. Test Results

In order to examine the proposed method and its effectiveness, a typical 6-bus power system is selected to apply the proposed method. The test system information is presented in Tables I and II.

TABLE I
6-Bus Test System Information

From Bus	To Bus	Length (mile)	Resistance (p.u)	Reactance (p.u)
1	4	60	0.15	0.6
1	5	20	0.05	0.2
2	3	20	0.05	0.2
2	4	40	0.1	0.4
3	5	20	0.05	0.2
4	6	30	0.075	0.3

At first, it is necessary to obtain the power flow results of power system in the base case. The load flow calculations have been taken by DIgSILENT software. The load flow results and three important characteristics of proposed objective function under base case have been presented in Table III.

TABLE II
6- Bus Test System Loads and Generations Data

Bus Type	Generation	Load (MW)	Load (MVAr)
PV	150	80	0
PQ	0	240	40
PV	360	40	0
PQ	0	160	24
PQ	0	240	40
Slack	600	0	0

The single line diagram of 6-bus test system is shown in Fig. 1. Also, the critical points of this test system according to three indices of the proposed objective function have been pointed in different color. As it seems, buses (2) and (5) have in desire condition in view point of voltage profile. Also, the congestion of lines (1), (4) and (6) is not desire and the phase angle of line (4) experiences an inappropriate condition based on stability index.

TABLE III
BASE CASE VALUES OF VOLTAGE PROFILES, TRANSMISSION CAPABILITY AND PHASE ANGLE

Bus No.	V_{init} (p.u)	VP_{init} (p.u)	Sending Bus No.	Receiving Bus No.	$P_{\max}^{init}$ (p.u)	δ_{init} (degree)
1	1.0000	0.0000	1	4	1.5831	10.7850
2	0.8699	0.1301	1	5	4.6987	10.9474
3	0.9999	0.0001	2	3	4.3491	9.3203
4	0.95	0.0501	2	4	2.0658	25.6717
5	0.9398	0.0602	3	5	4.6985	5.3809
6	1.0500	0.0500	4	6	3.3247	11.8411

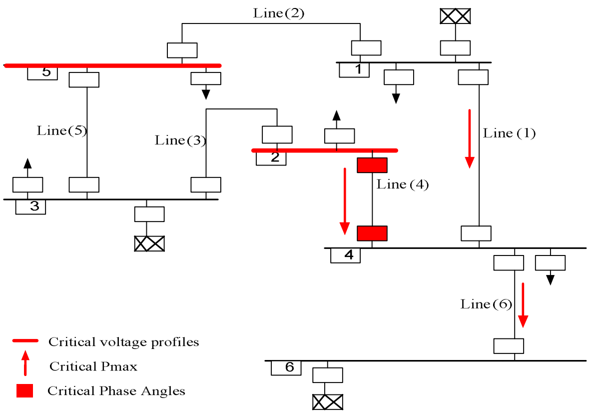

Fig. 7. Single line diagram of 6-bus test system and its critical points according three indices of the proposed objective function

According to some constraints such as expected budget, it is assumed that 3 STATCOMs can be implemented to improve the system parameters. The equivalent impedance model and sensitivity analysis have been used to calculate the effects of the installed STATCOMs and objective function. Afterward, the optimization problem is solved by using GA. GA has been implemented on optimization toolbox of MATLAB.

The optimization results are shown in Tables IV.

TABLE IV
OPTIMUM RESULTS OF STATCOMS ALLOCATION

Bus No.	VP_{comp}	Line No.	$P_{\max}^{comp}$ (p.u)	δ_{comp} (degree)
1	0.027	1	1.7253	10.383
2	0.091	2	4.6577	11.245
3	0.029	3	4.6777	8.855
4	0.027	4	2.3350	23.521
5	0.076	5	4.7551	6.963
6	0.040	6	3.4383	10.876

As shown in Table IV, the value of compensated voltage profiles and phase angles have been decreased to reach a better condition. Furthermore, the maximum transmission capability of lines has been increased.

The optimum objective function value is -0.524. Moreover, the optimal allocation of STATCOMs utilizes 3 STATCOMs located in buses (1), (5) and (6) with voltage values of '1.04', '0.94' and '0.92' p.u, respectively.

V. CONCLUSION

Optimal allocation of FACTS compensators like as STATCOMs effectively improves different parameters of power systems. Furthermore, required calculations such as power flow equations and modeling of FACTS controllers are time-consuming. Therefore, it is not applicable to apply the conventional approaches in order to solve the optimum allocation of FACTs. These facts will be more obvious, when the problem is studied on a large-scale test system. Hence, a novel approach is introduced based on sensitivity analysis and equivalent impedance model of VSCs. Since it is not required to solve a power flow in each iteration of optimization and modeling the FACTS accurately in the proposed method, it can be time-efficient and practical.

In this paper, STATCOMs are selected in order to compensate the system parameters and improve some system characteristics. The optimal allocation of STATCOMs in this paper is solved according to a novel objective function includes three indices such as voltage profile, transmission capability and stability. To solve the optimization problem, GA has been implemented on MATLAB.

The introduced approach has been applied on a typical 6-bus test system. The optimum results illustrate that this approach is useful to find the best allocation STATCOMs. It should be mentioned that it is possible to apply the introduced method to optimize the allocation of other FACTs controllers with some changes.

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