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ROBUST ALLOCATION OF FACTS DEVICES FOR IMPROVED TECHNO-ECONOMIC OPERATION OF POWER SYSTEMS

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ABSTRACT
In contemporary power system studies, the optimal allocation and utilization of Flexible AC Transmission System (FACTS) devices are important issues primarily due to their cost. In this study four types of FACTS devices (Static Var compensator (SVC), Thyristor-Controlled Series Capacitor (TCSC), Thyristor-Controlled Voltage Regulator (TCVR), and Thyristor-Controlled Phase Shifting Transformer (TCPST)) are optimally placed in a multi machine power system to reduce the overall costs of power generation. The placement methodology considers simultaneously the cost of generated active and reactive powers and the cost of selected FACTS devices. The Optimal Power Flow (OPF) and Genetic Algorithm (GA) based optimization procedure are employed to solve the allocation task. The Load Duration Curve (LDC) is used to ensure the robustness of the solution. Following the placement of FACTS devices in the system a small disturbance stability study is performed in order to assess the contribution of FACTS devices to system small disturbance stability. The study demonstrated that in addition to the reduction in the overall costs of power generation the allocated FACTS devices contributed to the improvement of damping of electromechanical oscillations.

KEY WORDS
FACTS, Genetic Algorithm, Cost Function, TCSC Modelling.

1. Introduction

The use of the FACTS devices in the power systems has been evolving ever since The Electric Power Research Institute (EPRI) introduced this technology, in 1980s. Several difficulties in power system operation can be overcome by selecting the appropriate FACTS devices as they offer, to some extents, additional degree of freedom over the influence of the system parameters such as series and shunt impedances, current and voltages [1].

Several studies were carried out to find the optimal placement of such devices in order to get the most out of their capabilities. For instance, studies [2-4] used OPF with additional algorithms to place different devices, however, none of them considered the devices cost. Other studies took into account the cost of FACTS devices [5-7] and showed that some FACTS devices are not only offering technical benefits to the network but are cost effective solutions. All of these studies however were considering steady state performance of the network.

In this study, the OPF and GA are firstly employed to allocate optimally four types of FACTS devices (SVC, TCSC, TCVR, and TCPST) to ensure the best techno-economic solution for the network in steady state. The study took into consideration the total cost of these devices (the cost of the device, the cost of installation and annual maintenance costs) and the cost of both, generated active and reactive powers. In addition, the annual Load Duration Curve (LDC) was used to suggest the operating conditions that will ensure the robustness of the allocation procedure. Following the placement of the devices a further investigation was carried out to assess the additional benefits that could arise from such allocation, namely the contribution of FACTS devices to small disturbance stability of the network.

2. Genetic Algorithm

Genetic Algorithm (GA) is a powerful numerical optimization algorithm used to reach an approximate global maximum (or minimum) of a complex multivariable function over a wide search space [8]. It has been used extensively in power system studies in the past [5,6,9,10].

A typical GA consists of the following four characteristic stages/attributes [11]:

1. A number of chromosomes (or individuals) included in a population, which represent a number of solutions to the problem given.
2. An authentic way to evaluate how good or bad each solution in the given population is. This step is quite important as GAs operate according to the principle of survival of the fittest, which means that the best individuals are more likely to participate in the generation process of the next population than the others.
3. A method that enables the creation of new individuals from the previous population.

4. An operator called *mutation*, which enhances the searching procedure.

The use of GA for placement of FACTS devices was well explained in [6,12], so, it is not repeated here. A Matlab GA Toolbox [13] was used in this study to solve the problem of optimal allocation.

3. Selection and Modeling of FACTS Devices

The power flow between any two buses in the power network is governed by three variables, i.e., bus voltage magnitudes and angles and the impedance of the connecting line. Based on this argument, three FACTS devices are selected, TCVR to control the bus voltage magnitude, TCPST to control the bus voltage angle and TCSC to control the transmission line reactance. In addition, an SVC is used to improve the overall network voltage profile. (Note: The change in the power flow results in the change of the reactive power (Q) demand in different areas of the network so the control of network voltages by remote or already Q limited generators may not be effective). Same of the devices considered in this study were used in [6], while in [12], the authors introduced Unified Power Flow Controller (UPFC) instead of TCVR.

Figure 1 below shows the steady state models of the selected FACTS devices. In addition, more details about the steady state models of FACTS devices can be found in [14].

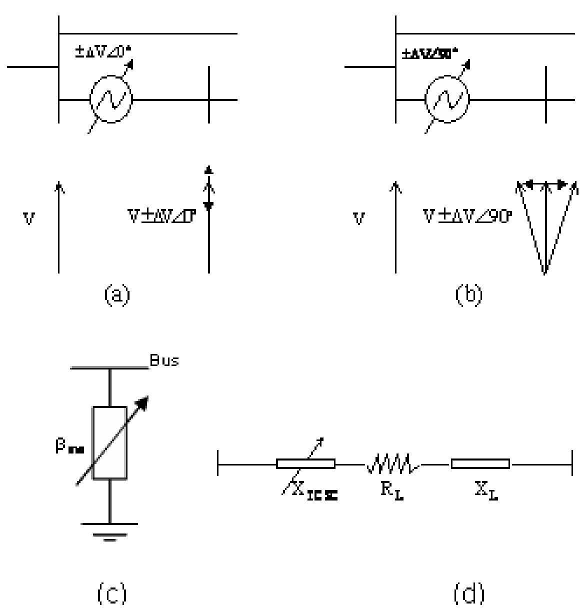

Figure 1: The steady state models of the selected FACTS devices. (a) TCVR, (b) TCPST, (c) SVC, (d) TCSC

The basic idea of TCVR and TCPST is to add an in-phase or a quadrature voltage component, respectively, to the bus of interest to introduce desired change in the bus voltage magnitude (in the case of TCVR) or phase angle (in the case of TCPST).

The main difference between them is in the way how the required voltage component is injected, i.e., in phase in case of TCVR or at an angle with respect to line voltage in case of TCPST [1]. The adopted range of TCVR turns ratio was 0.9 to 1.1, and the range of phase shifting of a TCPST was -5^o to 5^o. The phase shifting introduced by TCPST should not be too high since it may affect the voltage amplitude as well.

The SVC is modeled as a variable susceptance that can generate 150MVAr (capacitive mode) or absorb 100MVAr (inductive mode) at nominal (1.0 p.u.) voltage at the bus of interest. Finally, the TCSC is modeled as a variable capacitive impedance. Since the value of the X_{TCSC} is typically only a fraction of the transmission line reactance it is selected to be from $-0.2X_L$ to $0.8X_L$

4. Test Network

The network, shown in Figure 3, used in this study is the IEEE New England Test System, which consists of 39 buses and 10 equivalent generators. The network data are available in [15,16]. The bus voltage limits are set to be between 0.95 p.u to 1.05 p.u.

5. The Cost Functions of the Generators and FACTS Devices

The cost function of the real power (P) output of the generators is normally given in the form of a second order polynomial function as shown below:

$$C_P = \alpha_2 P^2 + \alpha_1 P + \alpha_o \quad (US\$/h) \qquad (10)$$

The α_i coefficients adopted in this study are α_0=0; α_1=40; α_2=0.01, for generators connected at buses 30-37, and α_0=0; α_1=20; α_2=0.03, for the remaining two generators at buses 38 and 39. The cost function of the reactive power (Q) output of the generators is given [17] by:

$$C_Q = \beta_1 Q + \beta_o \quad (US\$/h) \qquad (11)$$

with $\beta_1 = 0.01 * \alpha_1$ and $\beta_o = 0.1 * \alpha_o$ [16].

As far as the cost of FACTS devices is concerned, only typical cost functions associated with the total investment and infrastructure costs are considered. These costs are based on the curve fitting procedure applied to diagrams presented in [6, 18]. Based on these curves, the typical cost functions of an SVC and a TCSC are:

$$C_{SVC} = 0.0003S^2 - 0.3051S + 127.38 \ (US\$/KVAr)$$
$$C_{TCSC} = 0.0015S^2 - 0.713S + 153.75 \ (US\$/KVAr)$$

where S is the size of the FACTS devices in MVAr. Since the cost functions of generators are given in US$/h, the total cost of FACTS devices is converted to the same unit. It was assumed that the life expectancy of a FACTS device is ten years and that they operate 24 hours, 365 days per year thus, the total cost is divided by 10x365x24=87600.

In addition to the basic investment and installation costs, a maintenance cost of 5% (of the cost of the device) per annum is considered as well.

The cost functions of TCPST, and TCVR, are normally fixed and based on the rating of the circuit in which they are installed [5, 19]. The cost of these devices is therefore fixed at 100 US$/KVA.

6. Allocation Procedure

A total of 20 devices, i.e., five devices from each type, are considered in the allocation procedure in the study. Furthermore, the annual load duration curve, shown in Figure 2 below, is used to select the loading factors to ensure the robustness of the solution. Figure 2 shows the occurrence of the load demand over the year as a percentage of the system maximum demand.

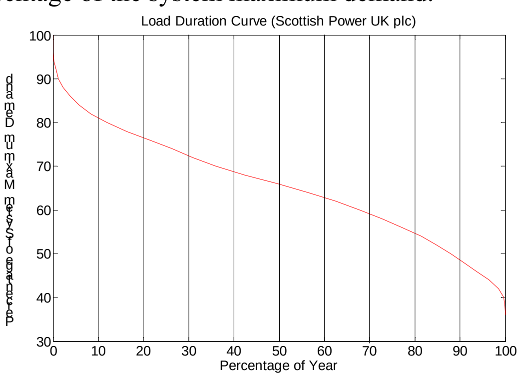

Figure 2 : Annual load duration curve

Based on the above figure, the following allocation procedure is adopted:

1. The optimal power flow (OPF) is run repeatedly with a gradual increase in the network loading factor until it did not converge. The non-convergence is a consequence of the violation of one or more constraints. The loading factor at the point of non-convergence was just above 1.182 p.u. for both active and reactive power. Table 1 shows the loading factors obtained for different operating conditions. (Note: The original loading factor of the network is 1 p.u.)
2. The GA algorithm is applied to optimally allocate available FACTS devices. There are two variables per device to be determined, the location and the rating. For the SVCs, 29 buses are considered as possible locations (excluding 10 generator buses) and the allowed rating was between 150 MVAr (capacitive) and -100 MVAr (inductive). For the placement of other FACTS devices all 46 lines in the network are considered as possible locations. As far as the rating limits are concerned they were as described above, i.e.: TCVR - turns ratio range from 0.9 to 1.1; TCPST - phase shift range from -5^o to 5^o; TCSC - range of X_{TCSC} variation from $-0.2X_L$ to $0.8X_L$.

Table 1: The used loading factors based on LDC

Operating condition number	Annual Loading – frequency of occurrence (%)	Loading Factor
1	0.01	1.182
2	10	0.96
3	20	0.90
4	30	0.845
5	40	0.816
6	50	0.78
7	60	0.733
8	70	0.686
9	80	0.638
10	90	0.567
11	100	0.426

3. A penalty factor is set to prevent placement of two SVCs at the same bus and two series connected devices at the same branch. The penalty factor increases the cost of placing the second device at the same location and discards such solution from further consideration.
4. The objective function (OF) is to minimize the generation cost while taking into consideration the cost of devices, i.e.:

$$OF = \min[\sum_{ii=1}^{OC}\left(\sum_{i=1}^{n}(C_{P_i} + C_{Q_i}) + \sum_{j=1}^{m} C_{FACTS_i}\right)]$$

Where C_P, C_Q and C_{FACTS} are the costs of active and reactive power productions and the placed FACTS devices, respectively. The indices n and m are the number of the generators and allocated FACTS devices, respectively. OC is the number of considered operating conditions, i.e., 11 in this case.

7. Results of FACTS Allocation

Following the above procedure it is found that only two TCSCs are required to achieve the maximum savings in the network, as shown in Table2 below.

Table 2 : FACTS allocation result

Type	Location	Rating (% X_L)	Saving
TCSC	Bus 16 – Bus19	-0.8	183 US$ / h
	Bus 25 – Bus26	-0.8	

The resultant saving shown in Table 2 is over all 11 loading factors, so, it is approximately 16.7 US$/h. Table

3 below shows the saving for each loading factor separately.

Table 3 : The network saving for each loading factor

Loading factor	Saving (US$ / h)
1.182	10.39126
0.96	12.53657
0.90	9.590513
0.845	6.853329
0.816	5.916105
0.78	4.885866
0.733	3.664797
0.686	2.60687
0.638	1.704097
0.567	0.148198
0.426	-2.16014

From the above table, it can be seen that the savings in generation costs in the network can be achieved with all considered loading factors except the minimum one (0.426). In this particular case, the presence of TCSCs in the network changes the generation dispatch adversely, i.e., increases the costs of generation.

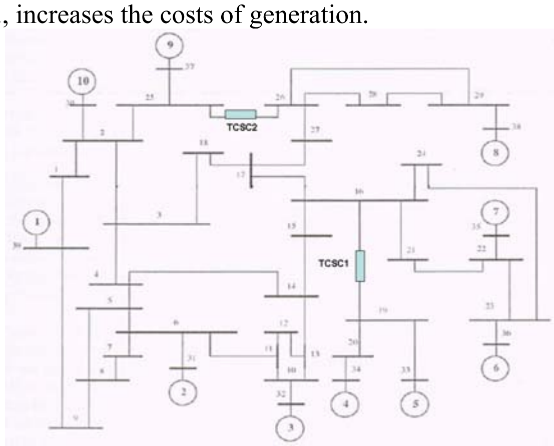

Figure 3 : IEEE New England Network with the optimal locations of the TCSCs

8. TCSC Dynamic Contribution

Following the optimal allocation of FACTS devices to reduce generation costs in the network, the influence of the allocated TCSCs on the small signal stability of the network is investigated. Only one operating condition is considered, i.e., the maximum system loading factor. Details about the network dynamic data including the Power System Stabilizers (PSSs) structure and parameter limits are discussed in [16, 20-21]. The objective function used in controller tuning process is given in [16]. It takes into account both, the real and the imaginary part of all electromechanical modes.

Generally, the function of the TCSC is to control the power flow in the transmission line in which the device is installed. This task can be accomplished automatically by using PI controller or manually by system operator [22-23]. Figure 4 shows the TCSC proposed model for the present study.

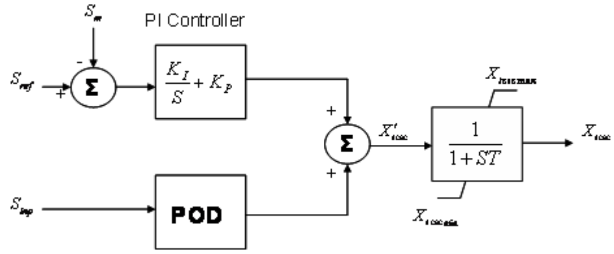

Figure 4: The TCSC dynamic model

The S_{ref} and S_m are the reference and measured signals for the PI controller, which controls the steady state TCSC impedance. The control action of this controller is slow and it takes more than 20 seconds to reach the target line power [23]. The S_{inp} is the input signal for the Power Oscillation Damping (POD) controller, which has the same structure as a PSS applied in generator's excitation loop. The input signal can be either locally or remotely measured signal. X'_{tcsc} is the output signal from the PI and POD controllers (If the PI controller is considered in dynamic study), which represents the input signal of the first-order lag block that emulates the natural dynamics of the TCSC device impedance [22, 24]. In the present dynamic study, the TCSC steady state impedance is assumed to be constant during the fault because of its slow action and in order not to interfere with the action of the damping controller.

All generators in the network are equipped with PSSs and the two TCSCs are equipped with POD controllers. Each one of them has three lead-lag blocks. All controllers are tuned using GA and the results are compared with the system dynamic performance without the inclusion of the TCSCs in the network in order to assess the dynamic contribution of these devices.

One of the important issues was the selection of the input signals for the POD controllers. By applying the observability study [25], the most effective input signals for POD1 and POD2 are found to be the real power output of generators 9 and 1, respectively. Although they are remote signals, they have the highest observability level for the poorly damped electromechanical modes of interest. For the PSSs installed at generators, the rotor speed deviations of corresponding rotors are selected as input signals.

Tables 4 and 5 below show the parameters of tuned controllers in both cases (without and with TCSCs in the network). $T_n i$ and $T_d i$ are the time constants of the numerator and denominator of the i^{th} lead-lag block.

Figures 5 and 6 show the active power output response of generators 2 and 5 after 2.5% sudden increase in the reference voltage of the excitation of generator 10.

It can be seen from the figures that the impact of TCSCs on system dynamics is significant and beneficial. This represents an incentive to apply FACTS devices, that already present in the network, for the improvement of network dynamic performance.

Table 4: The allocation of the PSS for the network without TCSCs (approximated to two decimal points)

Bus	Gain	Tn1	Td1	Tn2	Td2	Tn3	Td3
Gen1	11.5	1.11	5	1.39	1.92	5.24	0.51
Gen2	45.4	3.41	5.6	0.56	0.05	3.23	5.6
Gen3	32.6	4.65	5.6	2.48	5.6	0.95	0.39
Gen4	6.61	0.11	1.14	3.55	5.6	0.36	2.54
Gen5	0.05	0.98	5.6	0.59	5.6	1.26	4.01
Gen6	8.33	3.24	4.8	2.21	1.15	0.97	0.09
Gen7	5.64	5.34	4.71	0.18	1.24	0.43	1.24
Gen9	28	5.56	5.6	1.39	0.13	1.74	5.6
Gen10	19.3	0.58	0.07	0.23	0.99	0.62	0.08

Table 5: The allocation of the PSS for the network with TCSCs (approximated to two decimal points)

Bus	Gain	T_n1	T_d1	T_n2	T_d2	T_n3	T_d3
Gen1	35.59	0.12	2.13	0.54	4.07	5.17	2.67
Gen2	7.34	4.29	0.09	4.72	2.36	2.67	4.82
Gen3	34.10	5.32	7.65	1.40	2.87	0.60	0.1
Gen4	0.54	3.94	6.64	0.19	5.20	4.80	7.73
Gen5	17.02	0.44	0.09	5.37	3.11	2.36	3.42
Gen7	11.51	0.57	0.08	2.37	8.40	0.53	0.39
Gen9	5.17	0.39	0.12	1.95	0.32	4.28	4.29
Gen10	33.36	0.45	0.22	1.68	1.32	2.94	0.24
POD1	16.18	0.17	1.79	3.68	1.16	4.10	7.28
POD2	23.74	0.28	7.20	0.85	7.66	4.66	2.98

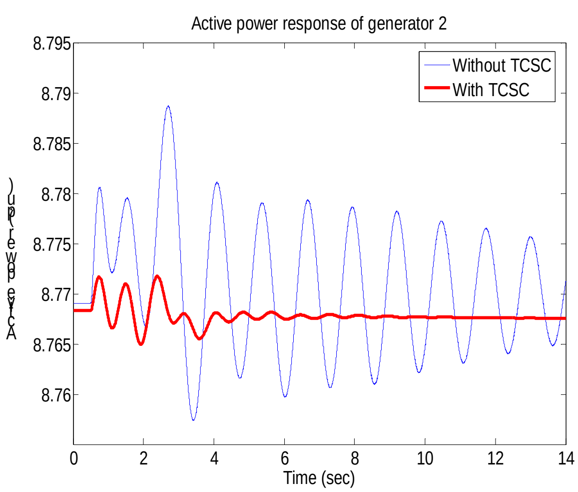

Figure 5: Active power response of generator 2

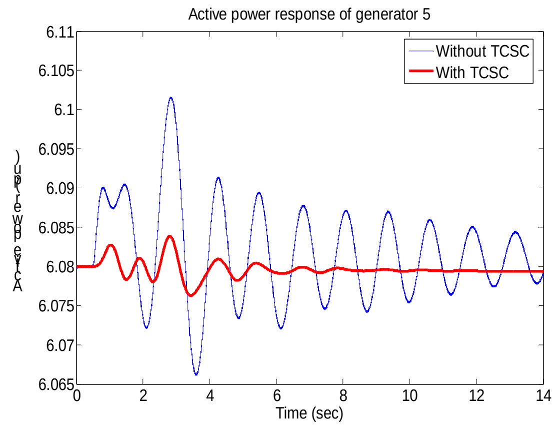

Figure 6: Active power response of generator 5

9. Conclusion

The paper demonstrated a techno-economic benefit of installing FACTS devices in the power system.

It showed that FACTS devices, a TCSC in this particular study, can help reducing the overall generation cost over different loading conditions and such result in direct savings to the network operator.

In addition to this, once present in the network, FACTS devices can enhance the system small signal stability performance if equipped with appropriately tuned damping controllers.

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