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Assessment of techno-economic contribution of FACTS devices to power system operation

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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 cost of selected FACTS devices for a range of operating conditions. The optimal power flow (OPF) and genetic algorithm (GA) based optimization procedure are employed to solve the allocation task. The net present value (NPV) method is used to assess the economic value of the proposed methodology. In addition to net reduction in generation cost allocated FACTS devices increased power transfer across the network and improved damping of electromechanical oscillations.

1. Introduction

Power transfer limits and directions in transmission system are constrained by thermal capacities of transmission lines (i.e., the material of the line) and voltage magnitude and voltage angle deviations across the line. In case of short lines the first limit that is typically reached is the thermal limit of the line governed by material of the line. In case of medium length lines the voltage magnitude at the receiving end reaches the statuary lower limit, i.e., drops typically below 0.9 p.u. or 0.95 p.u. (limit varies depending on voltage level and country), before the thermal limit of the line is reached and such limits further increase in power transfer. This is generally referred to as voltage stability limit which, if exceeded, might lead to improper operation or disconnection of end-user devices and ultimately to wide spread black-outs. Finally, in case of long transmission lines, voltage angle at the receiving end is the first that hits the limit and restricts further increase in power transfer due to endangered angular stability of the system. The thermal limits of the line are most difficult to alleviate as this would require change of material of the line (new conductors). Voltage and stability limits, however, could be increased by modifying line impedance and admittance and additional control of voltages and currents. FACTS devices offer possibility to influence line parameters (series and shunt impedances) and currents and voltages across the line and such increase allowed power transfer over existing lines without endangering system security [1]. Changes in power flows in the system, however, affects the generation scheduling and such could lead to different economics of power generation.

FACTS devices installed in existing power systems have been successfully used for several purposes including congestion management, reactive power support and enhancement of system damping. Their use has been evolving ever since the Electric Power Research Institute (EPRI) introduced this technology, in 1980s. Several studies, based on OPF calculations, were carried out to determine the optimal placement of such devices in the system in order to get the most out of their capabilities, e.g., [2,3]. Some of the previous studies [4–7] took into account the cost of FACTS devices as well, and showed that they could be a cost effective solution. Generally, there are still very few studies [8–10] of economic benefits arising from installation of FACTS devices.

The review of the past research identified that the economic contribution of FACTS devices was not thoroughly examined. There are a few studies, compared to the large volume of the researches in the area, that did consider the cost of FACTS devices though not in a comprehensive way that could justify the installation decision in a long run. Furthermore, these studies did not consider a wide range of operating conditions in order to ensure the robustness of the device installations. Moreover, a panoramic overview for the

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devices influence on the network in terms of economic, steady state and dynamic performances together was not studied.

This paper explores, in detail, both technical and economic benefits arising from the installation of FACTS devices with the emphasis on generation cost reduction. It builds on, generalizes and extends some of the approaches used in [9,10]. The OPF calculations and GA based optimization are employed to allocate four types of FACTS devices (SVC, TCSC, TCVR, and TCPST) in the system. The allocation objective, as never before, is based on cost function that includes cost of FACTS device, the cost of installation and annual maintenance cost, and the cost of both, generated active and reactive power. In order to propose a robust solution a range of operating conditions is considered. The annual load duration curve (LDC) is used for this purpose. The economic benefits arising from their installation are assessed using rigorous NPV calculations. It is recognized though, that the time scale for optimum scheduling of generation (to minimise the cost) is far too slow to justify alone the need for power flow control through thyristor controlled devices. The network constraints around the optimal generation dispatch could be reasonably well handled using fixed/switched compensation rather than expensive thyristor controlled devices which generally could be justifiable only for dynamic voltage and/or power flow control. Therefore, following the initial placement of devices guided by techno-economic merits of solutions, a further investigation was carried out to assess some of the additional benefits that could arise from installed FACTS devices namely, their contribution to power transfers in the network and small and transient stability of the network. In this way the techno-economic contribution of FACTS devices to system operation is assessed in most comprehensive way to date.

2. Genetic algorithm (GA)

Genetic algorithm (GA) is a powerful optimization algorithm used to reach an approximate global maximum (or minimum) of a complex multivariable function over a wide search space [11]. It has been used extensively in power system studies in the past [5,6,12,13]. A typical GA consists of four characteristic stages/attributes [14]: (1) a number of chromosomes (or individuals) included in a population, which represent a number of solutions to the problem; (2) an authentic way to evaluate how good or bad each solution in the given population is. This is an important step as GA operates according to the principle of survival of the fittest, i.e., 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. Details about the use of GA for placement of FACTS devices can be found in [6,8,15] and will not be repeated here due to space limitations. MATLAB GA Toolbox [16] is used in this study for optimal allocation of FACTS devices and for tuning of damping controllers.

3. Investment analysis

A comprehensive analysis of the investment in FACTS devices must include the capital cost or initial investment, the reduction in the generation cost resulting from the installation of FACTS devices, the operating and maintenance expenses and the economic life of the investment [17]. Several financial tools can be used to determine the financial benefit of the investment in FACTS devices [17]:

- *Simple payback*—A basic, but widely used method, of dividing the investment by the periodic project savings. This enables assessment of the time required to recover the initial investment.

$$n_{\text{year}} = \frac{\text{Cost}_{\text{FACTS}}}{\text{Annual\_Saving} - \text{Ma intenance}} \qquad (1)$$

- *Net present value* (*NPV*)—This method converts future costs and revenues to today's values to allow comparison to internal cash cost, or required rate of return. A positive number indicates that the project will have a positive return.
- *Life cycle costs* (*LCC*)—Utilizes NPV, but instead of analyzing a required rate of return, LCC only analyzes the costs associated with the life of project. The lowest LCC is preferred.
- *Internal rate of return* (*IRR*)—Also derived from NPV, however, this approach involves varying the discount rate until NPV goes to zero. A project with an IRR greater than the required (set) rate of return is worth pursuing.

This study focuses on evaluation of net present value as it takes into account all cash flows during the lifetime of a project. The considered cash flows are: initial investment and maintenance on the negative side and the saving in the generation costs on the positive side. The discount rate, *r*, on the capital investment has to be carefully chosen since the increase in the discount rate results in reduction of NPV. FACTS devices typically require a large initial capital outlay, however they could provide years of support with only reasonably small maintenance cost over their lifetime. The NPV can be calculated as:

$$\text{NPV} = \left[\sum_{t=0}^{T} \frac{CF_t}{(1+r)^t}\right] - CF_0 \qquad (2)$$

where T is the total time period of the project (in years), CF_t is the net cash flow at time t, CF_0 is the initial investment and r is the discount rate.

In this study the discount rate is set to $r = 10\%$, operating and maintenance cost per year are assumed to be 5% (of the price of device) and the economic life of devices $T = 10$ years (although many utility assets arguable have useful lifetime of 40–50 years [18]).

4. Selection and modelling of facts devices

The power flow between two buses in electrical power network can be controlled by adjusting bus voltage magnitudes, bus voltage angles and the impedance of the connecting line. In order to control those parameters four FACTS devices are considered in this study: TCVR to control bus voltage magnitudes, TCPST to control bus voltage angles, TCSC to control transmission line reactances and SVC to improve the overall network voltage profile. Same of them were also used in [6], while in [15], the authors introduced Unified Power Flow Controller (UPFC) instead of TCVR. Steady state models and detailed descriptions of considered devices are given in [19,20] and will not be repeated here due to space limitations. The basic principle of TCVR and TCPST operation is to add an inphase or a quadrature voltage component, respectively, to the bus of interest, and such introduce desired change in the bus voltage magnitude (TCVR) or phase angle (TCPST) [1]. The range of TCVR turns ratio adopted here is 0.9–1.1, and the range of phase shifting of a TCPST is -5° to 5°. (The phase shift 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 80 MVAr (capacitive mode) or absorb 80 MVAr (inductive mode) at nominal (1.0 p.u.) voltage at the bus of interest. The TCSC is modeled as variable capacitive impedance, X_{TCSC}. The value of X_{TCSC} is typically only a fraction of the transmission line reactance [1,6,15] and it is selected here to be between $-0.8X_L$ and $0.2X_L$.