DEVELOPMENT OF METAHEURISTIC ALGORITHMS FOR THE EFFICIENT ALLOCATION OF POWER FLOW CONTROL DEVICES

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# Chapter 1: Introduction

## 1.1. Background Information

The American electric grids are facing increasing issues, from the now yearly phenomenon of wildfires caused by fallen PG&E lines in California to the weeks-long outages in Texas in early 2021. While some of these issues are attributable to unexpected weather conditions, other issues such as congestion occur as supply and demand grow. Transmission congestion is a major issue in U.S. power grids. While there have been significant investments in congestion reduction (around US$40 billion in 2018), the congestion costs are still measured in the billions of dollars each year (US DOE 2020). As a way of mitigating the problem, variable-impedance series flexible AC transmission systems (FACTS) can help provide effective power flow control as part of smart transmission systems (Li, et al., 2010). FACTS devices can thus help improve the utilization of an existing network and provide a more reliable and sustainable power delivery network (Gotham & Heydt, 1998).

As an extension of the FACTS devices, and in order to improve deployability, Distributed FACTS (D-FACTS) are a lightweight version of FACTS. These have lower costs and possess the capacity of being re-allocated throughout their life to better respond to shifting needs. While traditional FACTS devices are installed at buses, D-FACTS can be installed throughout transmission lines or towers in a modular fashion (Sang & Sahraei-Ardakani, Effective power flow control via distributed FACTS considering future uncertainties, 2019). Thanks to these properties, D-FACTS devices are slowly becoming popular solutions to reduce line congestion in numerous electric grid improvement projects throughout the country (Kakkar & Agarwal, 2010). The capacity of FACTS devices to better integrate renewable energies has been previously demonstrated as detailed by Gandoman, et al. (2018). D-FACTS, however, haven't been studied

in such detail, although the expectation is that they will similary be very useful in the integration of renewable energies into existing grids.

### 1.2. Research Objective

Although arguably more versatile and effective, the allocation of D-FACTS modules rather than traditional FACTS devices introduces nonlinearities to the model which can be computationally exhausting to solve (Sang & Sahraei-Ardakani, 2018). Thus, the challenge is now not necessarily to optimally allocate the modules, but to do so in a computationally-efficient fashion. One of the main objectives of this research is to create algorithms which can allocate the modules in a quick, computationally-efficient way in order to optimize one or more objectives.

For this purpose, metaheuristic algorithms will be used in conjunction with other exact and heuristic approaches in order to minimize the computational time. After all, the benefits and applications of D-FACTS and FACTS devices have already been thoroughly proven (Gandoman, et al., 2018), so what is crucial now is to improve the optimization algorithms in order to hasten the allocation and implementation of these new technologies.

Thus, the main objective of this work is to create effective and efficient metaheuristic algorithms to optimally allocate D-FACTS modules on transmission systems based on improving one or more objectives to be studied, including operational costs and environmental impact metrics. These objectives may be optimized individually, that is, one at a time and with different results for each, or concurrently, at which point the allocation becomes a multiple-objective problem. There are multiple procedures for solving a multi-objective problem, such as using a utility function or with methods such as the NSGA algorithms. For this study, a non-dominated Pareto-optimal approach over Multiple Objective Evolutionary Algorithms will be implemented.

### 1.3. Scope and Limitations

The present work will analyze a number of electrical test systems, some of which are IEEE test systems. The systems may have undergone some slight modifications to be more suitable for studying the effects of D-FACTS modules on the system. If modifications are made, they will be specified and detailed as needed. Stochasticity is added to the systems in the forms of load scenarios, renewable energy capacity scenarios, and generation scenarios with the purpose of demonstrating the flexibility of the devices under different operating conditions.

This work aims to minimize total operational costs over the multiple scenarios for each case study, resulting in an increased profit for the relevant utility companies. Additionally, environmental impacts, in the form of Global Warming Potential (GWP) and Human Toxicity Potential (HTP) are to be minimized, resulting in better living conditions for surrounding communities. Other objectives, such as renewable energy integration will also be considered.

For the optimization process, this work will focus on the combination of evolutionary and linear programming algorithms to minimize computation time and improve the quality of the solutions. However, the scope of this research is limited to the generation of Pareto-Optimal solutions in multi-objective case studies, as the selection of the ideal solution is best left for an experienced decision-maker. Still, some methods for pruning the Pareto Set will be studied. In the case of single-objective optimizations, sensitivity analyses will be conducted on relevant variables.

The problems are studied under the assumption of static fuel costs and static investment costs and limits during an optimization run. Costs and emissions associated with energy generation and device installation are obtained from test systems data and not modified for the study.

### 1.4. Dissertation Outline

The remainder of this work will be structured as follows:

Chapter 2 will consist on a comprehensive literature review, to include topics such as FACTS and D-FACTS devices, optimization algorithms with an emphasis on those commonly

used for FACTS and D-FACTS allocation, multi-objective methods, and relevant mathematical models.

Chapter 3 will show previous publications by the author in the field, while chapter 4 will include mainly the mathematical formulations to be used in the study, including formulations found in research, for illustrative purposes. Chapter 5 will carefully detail the optimization algorithm used in the case study presented in chapter 6. Finally, chapter 7 provides some concluding remarks as well as future work directions.

## Chapter 2: Literature Review

### 2.1. FACTS AND D-FACTS

Flexible AC Transmission Systems (FACTS) and Distributed FACTS (D-FACTS) are thyristor-based controllers designed to manage series impedance, shunt impedance, phase angle, or some other parameter in electric transmission systems (Hingorani, 1993). Some of the most common types of FACTS devices are: Static Var Compensator (SVC) which are used to control the voltage of electric power systems; Thyristor Controlled Series Capacitor (TCSC) which is used to increase transfer capacity and system stability; Static Synchronous Series Compensator (SSSC), which is used for power transmission series compensation as a source of synchronous voltage; and Unified Power Flow Controller (UPFC), which can be used for enhancing steady state, dynamic, and transient stability (Murali, Rajaram, & Reka, 2010).

It has been repeatedly demonstrated that the installation of FACTS devices can not only improve the stability of the transmission networks, but also reduce operational costs and open the possibility for increased sales by utilities (Habur & O'Leary, 2004). They can also be installed with the more specific objectives of congestion relief and voltage stability (Wibowo, Yorino, Eghbal, Zoka, & Sasaki, 2011), in order to integrate different energy sources into the grid (De Oliveira, Marangon Lima, & De Almeida, 2000), or in order to improve security in the network (Yorino, El-Araby, Sasaki, & Harada, 2003).



#### 2.1.1. FACTS Allocation

The allocation of traditional FACTS has been thoroughly studied and algorithms for this purpose include Particle Swarm Optimization (PSO) (Jordehi, 2015), with some studies optimizing not only location but also device type and settings (Chansareewittaya & Jirapong, 2014). Additionally, the aspect of the network being optimized can vary from maximizing voltage stability during outages (Srivastaca, Dixit, & Agnihotri, 2014), optimizing power system loadability and minimizing installation costs (Malathy, Shunmugalatha, & Thaineesh, 2015), and

total operation and installation cost (Mohamed, Rama Rao, & Hasan, 2010). Genetic Algorithms (GA) have also been used in order to minimize cost (Cai, Erlich, & Stamtsis, 2004), simultaneous maximization of system security and minimization of installation costs (Radu & Besanger, 2006), optimization of branch loading, voltage stability and loss minimization (Surender Reddy, Sailaja Kumari, & Sydulu, 2010), power system security (Baghaee, *et al*. 2008a), among other objectives. Other optimization methods include Khan *et al*'s (2021) modified lightning attachment procedure optimization (MLAPO), a fairly novel metaheuristic algorithm; and the Firefly algorithm for reducing power loss, voltage deviations, fuel costs, and branch loading (Gundavarapu & Bathina, 2015). The results are fairly promising in reducing power losses and achieving quick convergence. Further details on optimization algorithms and methods are described in section 2.2.

### 2.1.2. D-FACTS Allocation and Benefits

Distributed FACTS, or D-FACTS, are a smaller, light-weight version of traditional FACTS. D-FACTS were proposed in 2005 with the objective of dealing with some of the obstacles that traditional FACTS have for deployment, namely the investment cost, space requirements, system stress, and reliability requirements (Divan & Johal, 2005). They have the added conveniences of being modular and re-deployable, not needing large spaces for installation at each bus, but their adjustance ranges are lower and the computational burden to optimally allocate them is larger due to the added variable of how many to allocate. Still, the potential economic benefit of D-FACTS is larger when compared to traditional FACTS (Sang and Sahraei-Ardakani 2018), not to mention the long-term benefit of re-deployability, which has not yet been studied in research, but promises reduced costs if a situation arises in which the network configuration changes and re-allocation becomes necessary.

The use of FACTS and D-FACTS devices also helps the integration of renewable energy sources into the power grid. Analysis has shown that FACTS devices can improve voltage profile at buses and reduce power loss in lines (Suresh & Sreejith, 2017). Smart grids are using FACTS

devices in order to improve power quality levels (Liao, Abdelrahman, & Milanović, 2016). It is estimated that by 2050 20-25% of energy in global grids will come from renewable sources such as solar, wind, etc. (Jha, Bilalovic, Jha, Patel, & Zhang, 2017). As such, power flow control devices will become more relevant in managing distribution networks and grid congestion. More than FACTS, D-FACTS are more attractive control devices to dynamically manage voltage, reactive power, and power quality (Gupta and Kumar 2016; Gaigowal and Renge 2016). It is important to note that due to the uncertainty that comes with the incorporation of renewable energy sources, precise and dynamic management of microgrids. D-FACTS-based green plug-switched filter capacitor filters have been developed to improve the energy use and dynamic voltage stabilization of wind energy-connected systems with load changes and temporary fault conditions, promising high-speed controllability and maintained power factor correction capability (Gandoman, Sharaf, Abdel Aleem, & Jurado, 2017). FACTS and D-FACTS technologies thus play a key role in the improvement of energy management as grids transition towards smart, dynamic control schemes (Gandoman, et al., 2018).



### 2.1.3. Mathematical Optimization Models for FACTS and D-FACTS

Similarly to the objectives being optimized, the formulations for the optimization models have also varied greatly between studies. Some studies have focused more on studying only what happens at transmission lines, thus disregarding some other aspects of the transmission systems such as spinning reserves or even costs, while other studies may be more interested in testing the integration of renewable energies, omitting things such as generator or line reliability.

Elmetwaly *et al*. (2020) modeled the integration of Adaptive Switched Filter Compensator (ASFC) and D-STATCOM type devices into a microgrid to improve power quality, specifically harmonic distortion and voltage stability in renewable energy sources, considering only the power sources and battery banks in their constraints as that was their focus of study, which had only 5 constraints in their optimization plus an objective function, with most of the article being devoted

to describing the renewable energy sources and the specifications used in the devices for their simulation. On the other hand, the study by Sang and Sahraei-Ardakani (2019) aimed to minimize total system operating costs considering power reserves and multiple stochastic scenarios, which needed to consider constraints for transmission capacities and voltage stability limits, thus resulting in a model with 21 constraints and an objective function, which resulted in a fairly realistic model for how a transmission network may operate.

Ultimately, the number of constraints in the model serves mainly to determine the computational burden that can result from using a solver and is no direct reflection of the quality of the model. The number of constraints does also help to estimate how many elements are being considered into the optimization but as every problem is different so will every study have a different formulation.

### 2.1.4. Types of D-FACTS devices

Some of the most common types of D-FACTS are the following: Distributed Static Compensator (D-STATCOM), which is useful for voltage regulation, compensation of current harmonics, control of reactive power, and uninterrupted supply from storage devices (Divan & Johal, Distributed FACTS - A New Concept for Realizing Grid Power Control, 2005); Distributed Static Series Compensator (DSSC), which allows for control of active line power flow, are smaller and cheaper than other types of devices, and help minimize real power losses (Divan, et al. 2004; Divan, 2005); Distributed Thyristor Controlled Series Compensator (D-TCSC), which helps improve system stability and development of cyber-secure control methods as well as controlling system voltages (Gandoman, et al., 2018); Distriubted Series Impedance (DSI) which can adjust line impedance for improving power flow (Divan & Johal, 2005); and Distributed Power Flow Controller (DPFC), a distributed version of the Unified Power Flow Controller (UPFC), which can control all parameters in a network including line impedance, power angle, and voltage magnitude,

with the added advantage of lower installation and maintenance costs and much higher reliability (Yuan, de Haan, & Ferreira, 2007). Out of these, DSI type devices will be used as the focus of the research, as the devices will be used to modify the line impedances to improve transmission capacity in order to optimize the various objectives studied.

### 2.2. Optimization Methods in FACTS and D-FACTS Allocation

The optimal allocation of indivisible items with connectivity constraints is considered to be at least an NP-hard problem (Igarashi, 2019). While there is no research studying the computational complexity of FACTS or D-FACTS allocation, it can be deduced based on the problem formulation that the computational time cannot be easily estimated on a polynomial time scale, and so we assume that the FACTS and D-FACTS allocation problem to also be at least NP-hard, if not NP-complete. Additionally, FACTS and D-FACTS allocation methods generally allocate the devices based on one of the following methods based on the objective to optimize: Sensitivity-based methods, cost-benefit analysis-based methods, voltage security margin-based methods, and optimization-based methods (Gupta & Kumar, 2019). While formulations such as linear programming or mixed-integer programming can be used to optimally solve complex optimization problems, they are faced with the drawback of large computational times. A popular alternative to reduce the computational burden is the use of heuristic and metaheuristic optimization methods. These may not be capable of guaranteeing an optimal solution due to their nature, but the solutions found are almost always at least very close to the true optimums. This section will focus on reviewing some of the most common optimization methods for FACTS and D-FACTS allocation problems, their base formulation, and modifications used in case studies.

### 2.2.1. Linear Programming

Linear programming (LP) is a method of achieving an optimal solution from a mathematical model which is expressed in linear relationships. While similar methods date back to Fourier, modern interpretation of linear programming are mainly attributed to George Dantzig, who designed the simplex method in 1947 (Chvatal & Chvatal, 1983). The standard form of a linear programming problem is expressed as follows:

$$\max\{\boldsymbol{c}^T\boldsymbol{x} \mid \boldsymbol{x} \in \mathbb{R}^n \wedge \boldsymbol{A}\boldsymbol{x} \leq \boldsymbol{b} \wedge \boldsymbol{x} \geq 0\}$$

Where **c** represents the vector of cost coefficients, **x** represents the vector of variables to be optimized, and **A** and **b** are the constraint coefficients and right-hand-sides in matrix/vector form.

In addition to linear programming, there are integer programming (ILP) and mixed-integer programming (MILP), where all or some of the variables in **x** are also constrained to integer space, increasing the computational complexity of the problem.

Many of the LP-based approaches to optimal FACTS and D-FACTS allocation use mixed-integer programming. Sahraei-Ardakani and Hedman's 2015 study proposed a mixed-integer reformulation of the nonlinear program in order to make the problem computationally solvable when optimizing FACTS allocation to improve system transfer capacity. MILP has also been used in order to optimize allocation and settings of FACTS devices to maximize system loadability in large networks, with simulations for networks up to 904 buses (Lima, Galiana, Kockar, & Munoz, 2003). Other authors chose to linearize the allocation problem into a standard LP formulation to relieve overloads and voltage violations (Shao & Vittal, 2006). Overall, it can be argued that different types of LP formulations are effective in solving problems in FACTS and D-FACTS allocation as well as Optimal Power Flow (OPF) problems. However, the fact remains that these

are at least NP-hard problems, and thus exact optimization methods such as this are not very efficient in finding a solution.

### 2.2.2. Branch and Bound Method

Branch and Bound is a heuristic search method. It was proposed in 1960 by Ailsa Land and Alison Doig as a method for solving discrete programming problems (Land & Doig, 1960). In essence, the algorithm consists of an enumeration of possible solutions in the form of a tree with the full set of possible solutions at the root and subsets at the branches. The algorithm then explores the branches and discards them based on their upper or lower bounds.

Due to the difficulty in finding upper and lower bounds for solutions of complex problems, branch and bound is not always a very popular choice for some combinatorial problems. However, it has been used in combination with Mixed-Integer Non-Linear Programming (MINLP) to find optimal allocation of SVC devices based on an Optimal Reactive Power Flow (ORPF) model. The study used branch and bound to restrict the solution space and then solved each sub-problem using the MINLP. By branching the problem, it was then possible to reduce the computational time of each solution (Alves Silva & Belati, 2016).



### 2.2.3. Particle Swarm Optimization

Particle Swarm Optimization (PSO) is a metaheuristic search method. Metaheuristics are high-level procedures designed to find or generate a lower-level search method which may provide a good solution to an optimization problem with limited information or resources (Bianchi, Gorigo, Gambardella, & Gutjahr, 2009).

Particle Swarm Optimization is a popular search algorithm thanks to its simplicity. It was originally proposed by Kennedy and Eberhart in the 1995 IEEE International Conference on