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Integration of Series FACTS into Interconnect-scale Production Cost and Long-term Planning Tools

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SUMMARY

The development of new series FACTS devices as well as the increasing difficulty of building overhead transmission lines in some regions is driving interest in deploying series FACTS devices to increase the transfer capability of the existing transmission network. As of late 2014, no known commercial tools could plan and simulate the operation of series FACTS devices in an interconnect-scale power system. Given this dearth and the new drivers for additional simulation capability, an existing power system simulation and planning platform called PLEXOS® was augmented to simulate five types of series FACTS devices. The capability was then demonstrated by using the platform to plan the deployment of series FACTS devices within a footprint consisting of the New York Independent System Operator (NYISO), ISO New England and a portion of the PJM Interconnection. This footprint is on the order of 14,000 buses and 2,500 generators. The results show that that series FACTS devices can be optimally planned for an interconnect-scale system and the operation of a deployment of series FACTS devices can be simulated for an interconnect-scale system.

KEYWORDS

Power System Planning - Power Flow Control - Flexible Alternating Current Transmission System (FACTS) - Production Cost Model – PLEXOS - Distributed Series Reactor (DSR) - Distributed Static Series Compensator (DSSC) - Static Synchronous Series Compensator (SSSC) - Thyristor-Controlled Series Capacitor (TCSC) - Mechanically-Switched Series Reactor (MSSR)

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INTRODUCTION

Series FACTS devices have been deployed for nearly two decades. Deployment has been primarily limited to controlling power on long, EHV transmission lines. Planning for and operating these devices was a tractable problem given the small number of viable locations. New series FACTS devices have emerged over the last decade that are more economical and deployable than the original series FACTS devices. In addition, new overhead transmission lines have become more challenging to build in some regions, increasing the demand for series FACTS devices to augment the transmission capability of the existing transmission network. Given these drivers, the set of viable locations for series FACTS has expanded and further complicated the process of planning and operating said devices. In addition, system planning and operation has become more complex given the emergence of renewable generation and additional stakeholders. The academic community has developed software tools to plan and simulate operation of the new series FACTS devices amidst the more complex environment [1-11]. However, said tools are generally not scalable to large, interconnect-scale power systems such as the Eastern Interconnection.

Multiple entities have developed tools to conduct production cost studies. These tools are typically run using a host of input data such as hourly demand profiles, fuel costs profiles, generator parameters such as heat rates and network data such as line impedances and ratings. The tools simulate the hydro scheduling, thermal unit commitment and economic dispatch stages to calculate the power system operating cost. Some of these tools have the ability to endogenously determine phase shifting transformer (PST) set points in addition to generator set points. Academic tools have been expanded to dispatch series FACTS devices but as of late 2014, no commercial tool existed to perform production cost studies for a system with series FACTS devices.

In addition, the academic community has developed planning tools to optimally select the type, location, timing and rating of an investment. Some of the existing tools allow selection of multiple technologies simultaneously, such as deployment of PSTs, deployment of demand response, construction of a new line and/or construction of a generator. Commercial tools require a more constrained set of choices such as building a new line or building generation but are able to accommodate larger systems. As of late 2014, no commercial tool supported the optimal planning of series FACTS devices.

Given the lack of a commercial tool able to simulate and optimally plan large, interconnect-scale power systems with series FACTS devices, an effort was initiated to model the new series FACTS devices in PLEXOS. PLEXOS is a commercial platform to simulate operation of the natural gas and electricity systems as well as plan said systems. Development was conducted to model three new power flow controllers in the tool, namely the distributed series reactor (DSR), the distributed static series compensator (DSSC) and the continuously variable series reactor (CVSR). Two existing power flow controllers were also modeled, namely the thyristor-controlled series capacitor (TCSC) and the mechanically-switched series reactor (MSSR). The production cost tool was augmented to enable endogenous decision of the set points of the series FACTS devices at each time step. The planning tool was augmented to allow endogenous decision of device type, location, rating and installation date to minimize the present value of fixed and operating costs over a user-defined study period.

To demonstrate the new capability, the production cost and planning tools were used to study the impact of series FACTS devices on the NYISO system. This study was conducted by simulating the operation of the interconnected system spanning NYISO, ISO New England and the classic portion of the PJM Interconnection. This area is on the order of 14,000 buses and 2,500 generators. The study included modeling of the unit commitment, economic dispatch and ancillary service stages while enforcing N-1 security constraints.

When run over the study area, the planning tool identified series FACTS investments that met the user-defined benefit-to-cost hurdle. Taking the identified series FACTS investments as an input, the production cost tool quantified the benefits of the investments over a multi-decade period.

This paper proceeds in five sections. First, the PLEXOS platform is introduced, then series FACTS devices are introduced, then the modeling of series FACTS in PLEXOS is discussed, then the NYISO case study is presented and finally conclusions are presented.

1. PLEXOS OPTIMIZATION

PLEXOS Integrated Energy Model (PLEXOS) is commercial software platform that combines mathematical optimization techniques with data handling, visualization and distributed computing methods, to provide a high-performance, robust simulation system for electric power, water and gas markets. The platform has been commercially available since 2000.

In PLEXOS, power and energy market elements are modelled with detailed properties and compiled to an integrated linear programming (LP) problem. A typical PLEOXS LP problem, as described below, determines the best production schedule, resource management and market trading strategies for the whole system. The mathematical solver is configured to find the global optimal solution of the LP problem.

Minimize: *Total system cost, including production cost, operation cost and transmission cost*
Subject to:
Power supply and demand balance
Fuel supply constraints
Production operation constraints
System reserve constraints
Emission constraints
Transmission thermal limits or stability constraints
Financial constraints

As well as short-term production planning, PLEXOS for Power Systems can optimize system expansion optimization, where the build cost, retirement cost, discount rate, tax schedule and depreciation schedule are added to the objective function of the optimization problem. By finding the best balance between investment cost and production cost, the long-term (LT) planning phase will provide the solution for new generator deployment, existing generator retirement, transmission network upgrade, etc.

All the constraints in the LP problem are linear equations, or linearized from non-linear curves, such as thermal heat rate curve and transmission loss model. In some cases, unit commitment (UC) dispatches, fuel availabilities, market block order executions or LT expansion decisions are required in the solution. In these cases, PLEXOS will add additional integer or binary variables into the LP problem, making it a mixed-integer programming (MIP) program. PLEXOS is able to solve large-scale (10,000+ nodes) system MIP problems over a long-term horizon (30+ years).

2. SERIES FACTS DEVICES

Series FACTS devices control power flow, and to a lesser degree terminal voltage, by changing the effective impedance of the line. Idealized devices consume no real power and thus operate in quadrature to line current but practical series FACTS devices have losses and thus require operating at an angle slightly removed from orthogonal to line current. Figure 1 and Figure 2 show circuit diagrams for two series FACTS devices, the static synchronous series compensator (SSSC) and the thyristor-controlled series capacitor (TCSC) respectively.

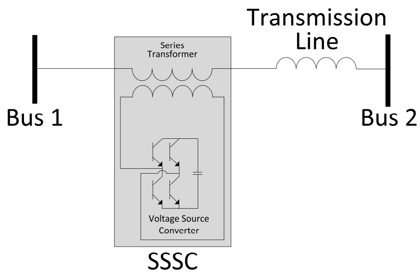

Figure 1: High-level topology of the SSSC

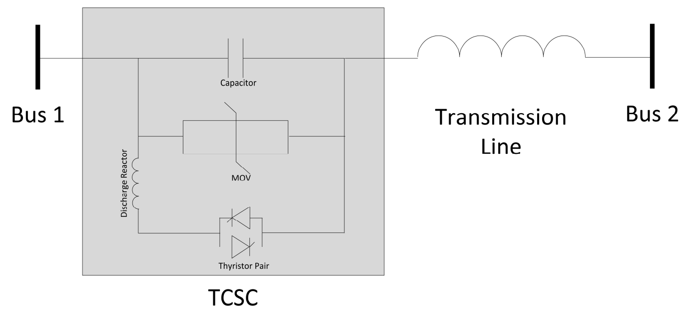

Figure 2: High-level topology of the TCSC

3. MODELING OF SERIES FACTS DEVICES IN PLEXOS

In order to achieve fast simulation speeds for large-scale power system systems, DC power flow assumptions were applied to the PLEXOS transmission model, in which contingency analysis, loss modelling and available transfer capacity (ATC) reporting were implemented to enhance the system simulation. It is desired to have the ability to optimize FACTS devices' deployment and assess their impact on system operation. A brand new object class has been implemented in PLEXOS, named Flow Control (FC). It is a replacement and extension of the existing Phase Shifter class, with more FACTS device types implemented. The flow models have been derived using DC power flow assumptions. Phase shifting angle is the major dispatch variable participating in overall optimization problem.

The power flow on a single branch with Flow Control device installed can be expressed as in (1).

$$f_{12} = \frac{\theta_1 - \theta_2 + \theta_{FC}}{X_{12}} \quad (1)$$

where θ_{FC} is the phase shifting angle on Flow Control,
θ_1 and θ_2 are the node phase angles on both ends of the branch,
X_{12} is the branch impedance,
f_{12} is the power flow on the branch.

The new Flow Control class can support a number of series FACTS devices, with different characteristics and modelling methodologies. A brief list is attached as below.

Distributed Series Reactor

The distributed series reactor (DSR) is a saturable reactor and therefore the maximum inductance of a fleet of units is current-dependent. The angle-flow curve is a nonlinear saturation curve, working as an extra constraint on the Flow Control phase angle variable.

$$\theta_{FC} = f(f_{12}) \quad (2)$$

In order to adopt DSR into linear optimization formulations, new properties Angle Points and Flow Loading Points were implemented in Flow Control to support user input curves. PLEXOS will make a piecewise linear approximation of the curve and linearize equation (2) in formulation.

Distributed Static Series Compensator

The distributed static series compensator (DSSC) is modelled as an AC voltage source in series with any given line. The voltage injected is fully variable within certain bounds. Specified max and min voltage are transferred to phase angle limits.

$$\frac{V_{min}}{V_{nom}cos\frac{\theta_1-\theta_2}{2}} \leq \theta_{FC} \leq \frac{V_{max}}{V_{nom}cos\frac{\theta_1-\theta_2}{2}} \tag{3}$$

where V_{nom} is the nominal voltage of the branch.

With the DC power flow assumptions that nodal phase angles are always small and negligible. It can be expressed as in (4).

$$\frac{V_{min}}{V_{nom}} \leq \theta_{FC} \leq \frac{V_{max}}{V_{nom}} \tag{4}$$

Static Synchronous Series Compensator

The static synchronous series compensator (SSSC) is modeled as a variable series voltage source, with allowable voltage ranging from negative max voltage to max voltage. Similar phase angle constraints are implemented as in (4).

Thyristor-Controlled Series Capacitor

The thyristor-controlled series capacitor (TCSC) is modeled as a current-dependent impedance that can be inductive or capacitive. Max and min impedance input are translated to phase angle limits.

$$\frac{X_{12}(\theta_1-\theta_2)}{X_{12}+X_{max}} - (\theta_1-\theta_2) \leq \theta_{FC} \leq \frac{X_{12}(\theta_1-\theta_2)}{X_{12}+X_{min}} - (\theta_1-\theta_2) \tag{5}$$

Mechanically-Switched Series Reactor and Continuously Variable Series Reactor

The mechanically-switched series reactor (MSSR) is able to inject discrete levels of inductance to achieve angle shifting between 0 and Max Angle. Equation (5) is implemented to model input impedance range [0, X_{max}]. The continuously variable series reactor (CVSR) is modeled like the MSSR but with a continuous inductance range.

4. CASE STUDY

Given high levels of congestion, the northeastern United States transmission network presents many opportunities for the deployment of series FACTS devices to aid in improving the local and regional transmission capability. As such, this region was selected to demonstrate the ability of PLEXOS to optimally plan the deployment of series FACTS devices and model the operation of said devices. As an aside, it is interesting to note the economic benefit of the deployment of series FACTS devices. The region of interest for this study was the NYISO and Tier 1 neighbors on the electrical grid. The following is a detailed description of the methodology, data, assumptions and results pertaining to this case study.

4.1 Methodology

The methodology of the case study at a very high level is in two stages. The first stage – Portfolio Selection – involves the selection of one or more portfolios of FACTS device deployments to study. The second stage – Benefits Evaluation – is the evaluation of benefits of the selected deployment portfolios to the transmission footprint over some representative time period.

Portfolio Selection entails an analysis of the long term financial viability of a collection of FACTS deployment candidates. This analysis estimates the optimal deployment of these devices given their capital costs, total production costs minus net market revenues and a view of the prevailing economic and electrical conditions affecting those costs. An optimal portfolio of such devices is selected based on superior financial viability at the portfolio level. Optimal portfolios can, in principle, depend on a wide range of factors which are structural (e.g. transmission topology), parametric (e.g. fuel prices, capital costs), time-dependent (e.g. forecast data on load or renewable build-out) or otherwise categorized. A description of the assumptions made on these factors follows. In this case, several optimal portfolios were produced by selecting a variety of capital cost values for the FACTS devices. As capital costs increase, the barrier to Portfolio Selection for each individual FACTS device is increased resulting in a collection of portfolios that exhibit increasing net benefit.

Once a collection of portfolios is identified, the Benefits Evaluation process computes a detailed estimate of the benefits attributable to each of the portfolios. This estimate is derived by means of comparing the production cost of a business as usual case (e.g. no FACTS expansion) to that of one or more FACTS expansion portfolio cases as determined by the Portfolio Selection process. The detailed estimate involves production cost simulation including the co-optimization of energy, ancillary services, transmission constraints and security constraints subject to chronological unit commitment and dispatch constraints of the usual sort. With this approach to benefits analysis, one may not only derive the *en masse* benefits of the portfolio, but also the incremental benefit-to-investment of an expanded portfolio with a lower capital cost hurdle.

4.2 Data and Data Sources

The data required to implement this methodology includes the most of the typical types of data for integrated generation and transmission production cost modeling. The transmission network model is the ERAG MMWG 2015_2013 series case. The generation data comes from Energy Exemplar's 2015 Eastern Interconnection (EI) dataset, including generator capacities and efficiencies, in particular Max Capacity (MW), Min Stable Level (MW), Average Heat Rates (BTU/kWh), Min Up and Min Down Times (Hrs), Max Ramp up and Ramp Down rates (MW/Min) and Variable O&M Charges ($/MWh). Generic start-up and shutdown costs by technology and fuel type are assumed for the generators in the study footprint. EIPC dual fuel data is used to model dual fuels for the entire Eastern Interconnect. Eastern Wind Integration and Transmission Study (EWITS) data from NREL is the basis for wind profiles for each of the wind generators in PJM, NYISO and ISO New England. A generic profile is used for solar profile for entire footprint under study. Generator retirement data has been collected from various public sources such as 2014 Gold Book for NYISO, CELTS report for ISO New England and the PJM website. NYISO PSTs, also known as PARs, are often modeled as members of the Transformer class, meaning their phase angle is fixed and unable to move over time. In this case study, the NYISO PARs are modeled as members of the Flow Control class, thus allowing them to be adjusted.

Hourly load profiles at the zonal level are used in this study. The energy and peak data for each zone comes from the website of the respective ISO.

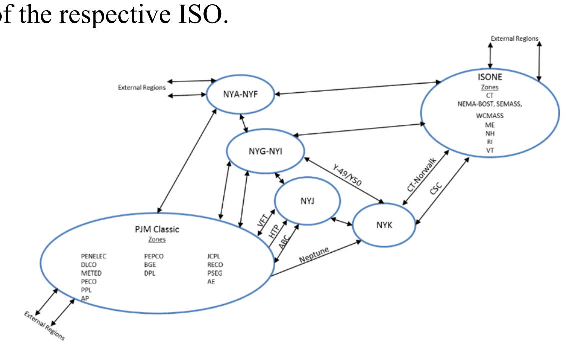

Figure 3: Representation of the study footprint: NYISO, ISO New England and PJM Classic

4.3 Additional Assumptions

The model for this case study was developed in PLEXOS. A number of additional assumptions were applied to the data to control the size of the optimization problem. These assumptions are described herein. The resulting implementation has the following overall characteristics.

	NYISO	ISO New England	PJM	Total
Buses	2821	4124	7428	14373
Lines	2536	2970	6974	12480
Interfaces	29	21	7	57
Zones	11	8	13	32
Generators	624	709	711	2044

Additional Assumptions: Transmission Topology

The transmission network data model only enforces constraints on buses and lines at 115 kV and above in the NYISO and New Jersey footprints and 345 kV and above for the rest of the model footprint. Figure 3 shows the study footprint. Interfaces are implemented to represent combined flow restrictions throughout the model footprint.

Additional Assumptions: FACTS Candidates

The FACTS candidates that are available to the PLEXOS model's Portfolio Selection process were input to the model based on the following selection criteria for the transmission lines that are modeled in the system. A line will be a candidate for FACTS deployment if it meets all of the following criteria:

- Not a transformer
- Reactance > 0.0002 p.u.
- Not an underground line
- Voltage greater than or equal to 34.5 kV and less than or equal to 345 kV
- Name does not end in 99 or EQ
- Has one or more terminals within NYISO

These criteria were primarily selected to ensure the candidate lines were compatible with installation of the initial version of the DSSC, which is intended for overhead lines with an operating voltage at or below 345 kV. The search was restricted to lines in New York to bound the scope of the demonstration.

Each candidate line meeting the criteria above was a candidate for deployment of power flow control devices ranging from +/-1 degrees to +/- 6 degrees of phase angle difference. The impact of the power flow controllers was then confirmed by simulating system operation using an 8760 hour analysis with N-1 contingencies enforced, marginal losses turned on and considering NYISO-ISO New England and NYISO-PJM hurdle rates.

Additional Assumptions: Dual Fuels

PLEXOS implements dual fuels as an economic decision between fuels based on market prices and fuel limits. Dual fuel mapping is determined by the EIPC dual fuel data.

Additional Assumptions: Power Flows to Zones outside the Study Footprint

The model uses historical data to represent power flows from zones outside of the study footprint.
In the case of this study, the flows in question are between ISO New England and Québec, ISO New England and New Brunswick, ISO New England and Nova Scotia, NYISO and Ontario and NYISO

and Québec. Also, some flows within the study footprint are fixed to represent common interregional flows

Additional Assumptions: Miscellaneous

A number of additional assumptions are employed to allow the simulation to reflect operational conditions of the system.

- Monthly hydro energy constraints are in place for each hydro generator in the footprint.
- Generic reserve requirements are implemented for the PJM Classic and ISO New England footprints.
- Actual reserve requirements are implemented for the NYISO footprint.
- FACTS devices in the study area, including Phase Shifting Transformers, are dispatched during each time step to minimize production costs.
- Interface limits and nomograms are fixed regardless of the penetration of FACTS devices.
- The study does not consider deployment of additional generation, AC transmission, DC transmission, demand response or energy storage.
- No post-contingency action is allowed, i.e. preventive Security Constrained Optimal Power Flow (PSCOPF). The list of N-1 contingencies includes all lines and substations with at least one terminal in NYISO and the nominal voltage of both terminals >=60 kV and <= 765 kV.
- The value of lost load (VoLL) (also known as cost of unserved energy) is assumed to be $10,000/MWh.

4.4 Results

The benefits under consideration that are quantified in this case study are production cost and ancillary services costs. In general, the benefits for a study of this sort are classified as follows.

Benefit Type	Description	Quantified
Production Cost	Day-ahead and real-time market simulation yielding production cost for the overall study footprint.	Only Day-Ahead benefits
Capacity Value	Increased transfer capability allows for the delivery of cheaper capacity from remote resources.	No
Ancillary Services	Ancillary services pricing is driven largely by the energy price, as it represents an opportunity cost for ancillary service providers. Reducing the energy price, lowers ancillary service prices.	Only Spin, no other products
Reliability	Technical benefits to assist with system reliability.	No
Public Policy	Public policy benefits support integration of renewables and environmental emission reduction benefits.	No

For the purposes of a quasi-benchmark, the actual outcomes of 2013 are compared against the results of the 2015 simulation model without FACTS devices. The resource mix in NYISO is similar, as shown in Figure 4 below, although with a shift from coal to natural gas.

NYISO - Total

UNIT TYPE	2013 ACTUALS	PLEXOS v20	DELTA
Coal	4,494	1,992	-2,502
Natural Gas	9,013	16,636	7,623
Natural Gas/Oil	48,830	44,635	-4,195
Oil	253	5	-248
Nuclear	44,756	45,064	308
Hydro	25,631	24,845	-786
Pumped Storage	766	484	-282
Wind	3,541	4,273	732
Solar	52	74	22
Other	3,003	2,269	-734
Net Imports	23,175	23,960	785
Total	**163,514**	**164,236**	**722**

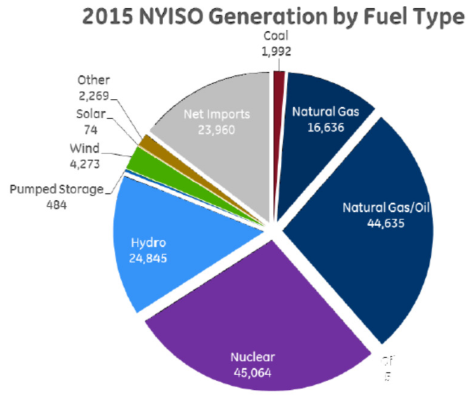

Figure 4: NYISO Generation by Fuel Type

Two Portfolio Selections entered the Benefits Evaluation stage, one in which the true build out cost was \$362 million and another in which the true build out cost was \$1,041 million. The first case produced \$77 million dollars per year of benefits yielding a Benefit-to-Cost ratio of 2.3 over 20 years. The second case produced \$80 million dollars per year of benefits yielding a Benefit-to-Cost ratio of 0.8 over 20 years. In each case, the aggregate discount rate was a discount factor of 0.54 over 20 years. The formula for Benefit-to-Cost ratio was

$$B2C = \frac{-\Delta PC \times 20\ years \times 0.54}{I_0} \tag{6}$$

Where *B2C* is the Benefit-to-Cost ratio, *ΔPC* is the difference in production cost between the case with FACTS devices and without (-*ΔPC* is the production cost savings) and I_0 is the initial investment i.e., the build cost.

The FACTS device portfolio has a significant impact on the flows on critical interfaces. When +/- 15 degrees of FACTS devices are deployed on the UPNY-SENY interface in the simulation, the flow adjustments in Figure 5 are observed, resulting in significant benefit accrual during the periods of flow enhancement.

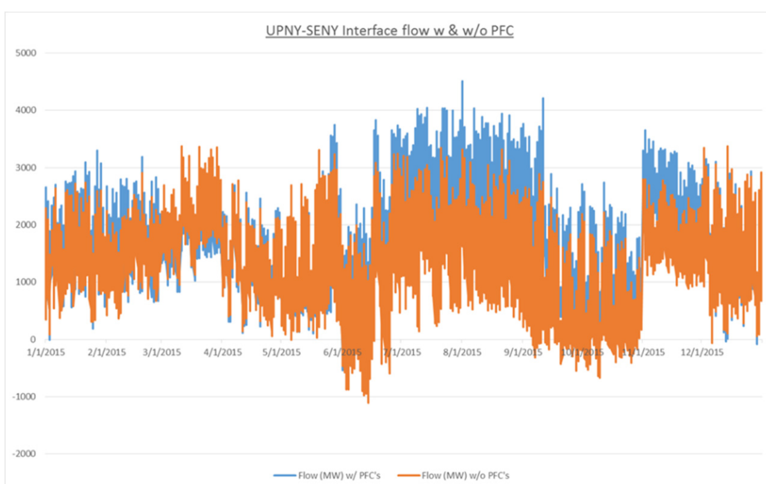

Figure 5: UPNY-SENY Interface flow comparison for the case with FACTS devices (PFC) and without

5. CONCLUSIONS

A commercial power system simulation and planning platform, called PLEXOS, has successfully been augmented to model series FACTS devices. The modeling capability has been demonstrated by planning a deployment of series FACTS devices in the Eastern Interconnection of the U.S. and then quantifying the benefits of said deployment. Given the assumptions made for the demonstration, the results indicate that the series FACTS can reduce the sum of production cost and capital cost for the study footprint.

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