Flexible AC Transmission Systems (FACTS) and Power System Security — A Valuation Framework

Spyros Chatzivasileiadis, *Student Member, IEEE,* Thilo Krause, *Member, IEEE,* and Göran Andersson, *Fellow, IEEE*

***Abstract*—Considering aging power system infrastructures in conjunction with increased electricity trading activities, there is a strong need for future investments in electricity grids. Technological progress has made available a number of different investment alternatives, ranging e.g. from "standard" reinforcements of existing transmission capacities to the installation of Flexible AC Transmission Systems (FACTS). This paper proposes a framework for comparing different investment alternatives. The approach relies on an optimal power flow (OPF), where system security is explicitly considered by means of a novel formulation for a security constrained optimal power flow (SC-OPF). For evaluation purposes several indicators are proposed, such as the loading of transmission lines, the total generation costs and the overall dispatch depending on different consumption levels. In a first case study the installation of shunt and in-series FACTS devices are compared. The paper is concluded with a sample valuation assessing whether to invest in a Thyristor-Controlled Series Capacitor (TCSC) or in a line reinforcement, i.e. additional line capacity.**

***Index Terms*—transmission expansion planning, optimal power flow, security-constrained optimal power flow, Flexible AC Transmission Systems (FACTS), investment valuation**

I. Introduction

In EUROPE, substantial investments in national power system infrastructures have been made in the 1960s and the 1970s. With a usual depreciation range of 40 to 50 years, a growing share of grid assets approaches the end of its nominal lifetime. It is obvious that there is a growing need to invest in electricity infrastructures, not only for the replacement of aging equipment but also to extend the grid capabilities in order to facilitate increasing national and trans-national electricity trade. The latter has been further stimulated by legislations of the European Union aiming at the creation of a truly internal European energy market [1]. However, the building of e.g. new transmission lines or new generation sites has to satisfy also the interests of the public and to match environmental criteria. Hence, prospective network investments should ideally be evaluated in a coherent manner, demonstrating the advantages and disadvantages of certain alternatives from a societal viewpoint and also from a system security viewpoint. Such an assessment would reflect at least two major objectives being cost or welfare efficiency and a secure and stable operation of the network.

Technological progress has made available a number of different investment possibilities, ranging e.g. from "standard" reinforcements of existing transmission lines to the installation of Flexible AC Transmission Systems (FACTS). To study these alternatives from an economic and from a system security viewpoint, an optimal power flow approach seems adequate. A security-constrained optimal power flow (OPF) based on DC approximations can nowadays be regarded as standard planning tool [2], [3]. However, such a DC-OPF does not seem to reflect the properties of FACTS devices in an appropriate manner, as these devices have also an influence on voltage levels, reactive power etc. Unfortunately, the complexity of a full AC security-constrained OPF including FACTS devices is high. Several publications have targeted this problem. In [4] the most severe contingency is taken into account; another possibility would be to include AC Power Transfer Distribution Factors [5], but this would also significantly increase the complexity.

In contrast with these approaches, the contribution of this paper is a hybrid formulation of a security-constrained optimal power flow (SC-OPF) combining a full AC optimal power flow with sensitivities derived from a DC model – which take into account security constraints – and including FACTS devices. The formulation allows to study any possible contingency (line or generator) without the need to focus on worst-case contingencies. Furthermore, we propose a valuation framework to compare in-series and shunt flexible AC transmission systems, as well as transmission line upgrades, and identify their effects on system security and overall generation costs.

The remainder of the paper is structured as follows. Section II describes the formulation of the security-constrained optimal power flow (SC-OPF), presenting the necessary extensions in order to include also FACTS devices. In Section III the valuation framework is briefly sketched, where we demonstrate the applicability in subsequent case studies (Sections IV, V). The paper is concluded with a sample valuation assessing whether to invest in a Thyristor-Controlled Series Capacitor (TCSC) or in a line reinforcement, i.e. additional line capacity taking into account a realistic load profile (Section VI).

II. Formulation of the Security-Constrained Optimal Power Flow (SC-OPF) Including FACTS Devices

The problem setup is presented in three steps. First, the standard formulation of an AC optimal power flow is described. In a second step the optimization problem is extended to include FACTS devices. Lastly, it is shown how system security is incorporated in the optimal power flow. The overall objective

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of the proposed framework is to evaluate the contribution of FACTS devices to the secure and economic operation of power systems.

A. Standard AC Optimal Power Flow (AC-OPF)

The objective of the standard AC Optimal Power Flow (AC-OPF) is to minimize total generation costs (see Eq. 1). The AC-OPF is implemented as follows:

$$min \sum_{j=1}^{N_{gen}} C_j(P_{G_j}) \tag{1}$$

subject to:

$$f(\theta, V, P, Q) = 0, \tag{2}$$
$$P_{min,i} \leq P_{gen,i} \leq P_{max,i}, \tag{3}$$
$$Q_{min,i} \leq Q_{gen,i} \leq Q_{max,i}, \tag{4}$$
$$V_{min} \leq V_{bus,i} \leq V_{max}, \tag{5}$$
$$\theta_{ref} = 0, \tag{6}$$
$$|S_{ij}(\theta, V)| \leq S_{ij,max}, \tag{7}$$
$$|S_{ji}(\theta, V)| \leq S_{ji,max}. \tag{8}$$

Eq. 2 represents the power flow equations as described in [6] and [7]. The remaining constraints refer to the active and reactive power limits of the generators (Eq. 3, 4), the voltage limits of the nodes (Eq. 5) and the line power transfer limits (Eq. 7, 8). Eq. 6 is added, defining the slack bus, where the phase angle is set to zero [2].

B. Additional Constraints for the Inclusion of FACTS devices

In a subsequent step, the AC-OPF can be extended with four additional constraints in order to take into account the effects of controllable devices on the OPF solution. In this paper, shunt and in-series connected FACTS devices have been considered. The capabilities of the modeling framework are demonstrated with a single series connected FACTS device, namely a Thyristor-Controlled Series Capacitor (abbreviated TCSC) and with a single shunt FACTS device, the Static Var Compensator (abbreviated SVC). The proposed framework can also be applied to other device types, provided that appropriate device characteristics are considered.

Eq. 9 models the TCSC as a variable reactance connected in series with a transmission line. The SVC is modelled as a variable shunt susceptance. The reactive power injected by the SVC at bus n is given by Eq. 10. The limits of the individual devices (TCSC or SVC) are determined by the constraints (11) and (12).

$$r_{ij} + jx_{ij} = r_{line,ij} + j(x_{line,ij} + x_{TCSC}), \tag{9}$$
$$Q_{SVC,n} = -b_{SVC,n} V_n^2, \tag{10}$$
$$x_{TCSC,ij}^{min} \leq x_{TCSC,ij} \leq x_{TCSC,ij}^{max}, \tag{11}$$
$$b_{SVC,n}^{min} \leq b_{SVC,n} \leq b_{SVC,n}^{max}. \tag{12}$$

C. N-1 Security Constraints

The contribution of controllable devices to the security of the power system is evaluated by taking into account the N-1 security criterion. This criterion, in its simplest form, says that the system should be able to withstand the loss of any single component, e.g. line, generator, etc., without jeopardizing the system operation [8]. Most power systems in practice are bound to operate in a N-1 secure state.

Common formulations of OPF-problems either do not consider the N-1 security criterion or assume that the line limits are set to a value such that the system remains always N-1 secure. An optimization problem which explicitly takes into account outage events is usually referred as a Security-Constrained Optimal Power Flow (or SC-OPF). When comparing the solution of a standard OPF and an SC-OPF, the cost of redispatching the generators in order to ensure an N-1 secure state can be easily calculated. We will refer to this cost difference as "cost of security".

Incorporating the N-1 security criterion means that additional constraints should be introduced, calculating the line loadings when an unplanned outage of either a single transmission line or a generator occurs. The objective is to find a least-cost generation dispatch such that an outage of an arbitrary line or generator will not lead to overloadings at any point in the system.

For the implementation of an SC-OPF different approaches exist. Usually, a standard OPF is solved, followed by a contingency analysis which determines the critical overloadings. Then these constraints are added in the initial OPF problem and the OPF is solved again [2]. Another possibility is to rely on DC approximations. Such security-constrained DC-OPF approaches can also be found in the literature (see for example [3], [2]). The advantage of solving a DC-OPF problem is that constraints for line and generator outages can be included in the OPF as linear sensitivities. With the help of Power Transfer Distribution Factors (PTDFs), the Line Outage Distribution Factor (LODF) and the Generalized Generation Distribution Factor (GGDF) can be calculated. LODF and GGDF allow to determine the loading of each line in case of an outage. However, when it comes to solving an AC-OPF, these sensitivities are no longer linear and it is not straightforward to include them in the OPF problem.

An approach followed in [4] and [7], introduces a second set of power flow equations and constraints, in order to incorporate "critical" conditions associated with the maximum loading margin. In this way, the N-1 criterion is being considered by taking into account the overloading, which occurs during the most severe line outage.

In this paper we propose a different approach. The linear sensitivities, calculated through a DC approximation of the power flow equations, are included in the optimization constraints. Constraints (13) and (14), quantify the effect of line and unit outages on the remaining system lines.

$$\left| \frac{1}{x_{ij}}(\theta_i - \theta_j) + LODF_{ij,mn} \cdot \frac{1}{x_{mn}}(\theta_m - \theta_n) \right| \leq F_{ij}, \tag{13}$$

for all monitored lines ij and outaged lines mn.

$$\left|\frac{1}{x_{ij}}(\theta_i - \theta_j) + GGDF_{ij}^k \cdot P_k\right| \leq F_{ij}. \quad (14)$$

A calculation of the line loadings by the full AC model would be more precise than through the constraints (13) and (14). However, the results are still a good approximation of how the generators should be dispatched to find a N-1 secure system state, while the computational complexity is significantly reduced.

The term F_{ij} is the short time emergency overload rating of the line ij and is usually $10-20\%$ greater than the continuous rating S_{ij} [3]. $LODF_{ij,mn}$ is defined as the fraction of the power flowing on line mn before it is outaged, which now flows over line ij due to the line mn outage. The $LODF$ is given by [2]:

$$LODF_{ij,mn} = \frac{x_{mn}}{x_{ij}} \cdot \frac{X_{im} - X_{in} - X_{jr} + X_{js}}{x_{mn} - (X_{mm} + X_{nn} - 2X_{mn})}, \quad (15)$$

where x_{ij} is the reactance of the line ij and X_{im} is the entry in the ith row and mth column of the bus reactance matrix $\mathbf{X}$.

$GGDF_{ij}^k$ is defined as the fraction of generation of unit k before it is outaged, that flows over line ij after the outage of unit k [9], and is computed as follows:

$$GGDF_{ij}^k = \frac{1}{x_{ij}} \mathbf{1}_{ij}^T \left[\mathbf{B}\right]^{-1} \mathbf{r}_k, \quad (16)$$

where $\mathbf{B}$ is the admittance matrix for the DC power flow equations and $\mathbf{1}_i$ is the ith singleton vector (i.e. $\mathbf{1}_3 = [0010...0]^T$), with $\mathbf{1}_{ij} = \mathbf{1}_i - \mathbf{1}_j$; $\mathbf{r}_k$ is a vector having value -1 at the kth row and $P_i^{max} / \sum_{j \neq k} P_j^{max}$ at all other rows, i. Here, it is assumed that the lost generation of unit k, P_k, is distributed to the remaining system units in proportion to their nominal power output[1] [3].

III. Valuation Framework

A. Framework Overview

Above an optimal power flow problem has been formulated capable of assessing FACTS devices and their influence on system security. Such an OPF approach sets also the prerequisites for the valuation framework. The OPF aims at an overall system view, i.e. investments such as FACTS devices or additional transmission capacities are evaluated in terms of their effect on total generation costs. This view might be close to the perspective of a regulating authority, targeting the efficient functioning of the overall system including both: the generation side as well as the network. The latter can be evaluated in terms of the loading of individual lines, i.e. how FACTS devices change the power flows in the system. This information gives a picture of network utilization, where it is also possible to study the differences between a "standard" OPF and a security-constrained OPF. Note that in practice the system should operate according to the solution of the SC-OPF. Comparing the solutions of the two algorithms, the cost of system security can be explicitly evaluated. In summary it can be said that we focus on total generation costs, the overall loading of the system and the loading of individual lines in the system (congestion) to compare different investments. Complementary assessments are made to quantify the inclusion of system security in the OPF formulation and the effects of different consumption levels.

B. Return on Investment vs. Net Present Value

When it comes to valuation it seems meaningful to also apply standard monetary measures originating from investment science. One of the best known concepts is the net present value (NPV). It takes investment cost, future earnings caused by the investment, the asset lifetime and an expected interest rate as input and calculates the value of the investment as of today. If the NPV is positive, i.e. above zero, the investment is profitable as it generates a profit over its lifetime. In our simulations we have found that the NPV is not an illustrative measure to compare e.g. the profitability of FACTS or transmission lines. As we follow an overall system perspective, the savings in generation cost (which might actually be seen as an income) are that substantial that the NPV becomes positive after a short period of operation time (usually three to four years). This means that any investment taken will be profitable. Thus, we opted for a monetary indicator similar to the return on investment (ROI). We divide the annual savings achieved by a certain investment alternative (line upgrade, building of a TCSC) by the total investment cost. In that, we define an indicator on a percentage basis that determines the annual savings per monetary unit invested. In our simulations typical values range from e.g. 0.3 to 0.5. This means that per each Euro invested in a certain transmission reinforcement you save annually 0.3 to 0.5 Euros in return.

IV. Valuation of FACTS devices

Fig. 1 shows the 10-bus power system used to study the influence of FACTS devices on system security and generation costs. The system is similar to the one used in [6] and [10]. It emulates to a certain extent the interconnecting flows between Switzerland, France and Italy. The system data are available in the Appendix. Large production units are installed in the top left area. The generator on bus 3 is representing aggregated production of nuclear units. Generator 5 is an aggregation of conventional thermal units. The generators on buses 2 and 7 represent hydro power installations. Generator 8 in the lower right part of the network has high production costs. Large loads are located at buses 3, 7, 8, and 10, forming two main load areas: one close to the production in the top left part of the network and one in the lower part close to the expensive thermal generator number 8. The power factor of the loads is assumed to be the same on all buses amounting to $cos\phi = 0.95$ inductive. Due to the differences in production costs the power flow in the network is generally from the top left towards the bottom right. One type of series and one type of shunt FACTS device (a TCSC and an SVC respectively) have been

[1]Note that constraint (14) calculates the line loadings in the event of a generator outage but does not take into account if each of the remaining generators has the capacity to supply the necessary additional power. In the present paper we have assumed that all the generators have additional reserve capacity, beyond their P_{max} limits, which can be utilized in case of a contingency.

selected for the following studies. The framework however can easily accommodate any controllable device type (e.g. a Phase-shifting transformer, a STATCOM, etc.). The TCSC is assumed to be able to vary up to 60% the transmission line reactance, while the SVC has a capacity of 170 MVAr. The emergency overload rating F_{ij} has been assumed 20% higher than the continuous line rating.

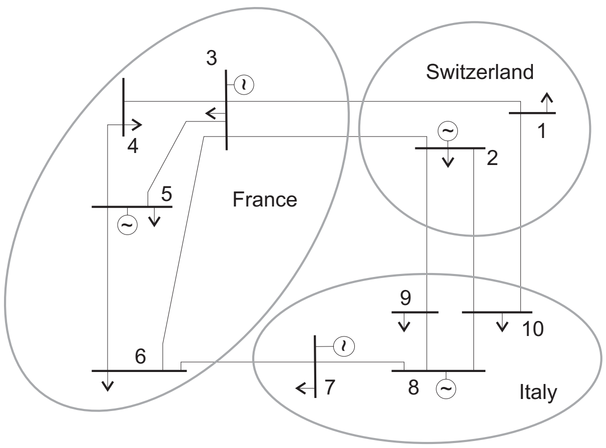

Fig. 1: 10-bus network used for the simulations.

A. Comparison of Line Loadings

For the following comparison the loads on each bus are assumed to consume 100% of their nominal power. Four different cases are examined. The focus is on line loadings and how these are influenced in case a FACTS device is installed and/or the N-1 security criterion is considered.

First a standard AC-OPF is solved. Then, a TCSC is introduced in line $6-7$ and the line loadings are recalculated.[2] Taking into account the N-1 security criterion an SC-OPF is solved, with and without the series FACTS device in line $6-7$. The results are shown in Fig. 2 and Table I. In the case of a standard OPF, the FACTS device relieves congestion on Line $2-10$, allowing at the same time more power to flow through lines $5-6$, $6-7$, $7-8$ (from Generators 3 and 5 to the loads in the lower right part). Similar observations can be made when comparing the solutions of the SC-OPF. However, having to take into account all possible outages, the SC-OPF delivers significantly lower loadings of almost all lines in comparison with a standard OPF. As far as generation costs are concerned, they are higher as the inclusion of security constraints results in a more expensive dispatch of the generators (see Table I). Although the solution of the AC-OPF is acceptable for the system, in reality the TSO must ensure that the system is N-1 secure. Hence, the generators should be dispatched according to the SC-OPF solution. The difference of about 30 k€/h represents the "cost of security". Observe, however, that with the inclusion of a TCSC, the reduction in generation costs is about 3 times higher in the SC-OPF than in the standard AC-OPF. The cost of security, in this case, decreases and equals 21.7 k€/h. A general remark from our studies is that when security constraints are considered, a FACTS device has a significantly more positive effect on the total costs reduction.

[2]The TCSC has been placed in line $6-7$ as this location had the highest influence on generation costs, as it allows more power to flow from the cheap generation area in the top left to the large loads area in the bottom right. Therefore, in this line the "cheapest" dispatch solution could be obtained.

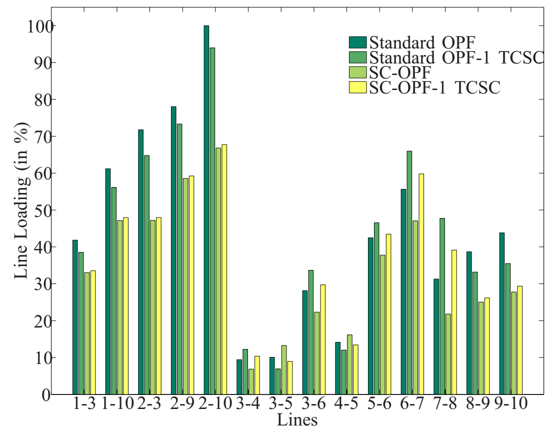

Fig. 2: Line Loadings for four different cases.

TABLE I: Generation Costs (in Euro/h)

Standard OPF	Standard OPF 1 TCSC	SC-OPF	SC-OPF 1 TCSC
326'425	321'936	356'348	343'626
Reduction	1.38%	Reduction	3.57%

B. Effect of Different Consumption Levels in the SC-OPF

In the following, the contribution of FACTS devices depending on different load levels is evaluated. Assuming that the *load* values in Table II (see Appendix) correspond to maximum values, snapshots ranging from 10% to 100% system load are examined. For each snapshot the loads at all buses were assumed to decrease by a given percentage rate in a uniform manner. Five different cases are investigated, all solved with the SC-OPF. Except for the base scenario (no FACTS device), cases reflect the following:

- the installation of an SVC on bus 10
- SVCs on all buses (10 SVCs)
- a TCSC in line $6-7$
- TCSCs on all lines (14 TCSCs)
- a combination of TCSCs and SVCs.

The results are illustrated in Fig. 3. In Fig. 4, the percental reduction of the total system costs with respect to the base scenario is presented.

When the system is not heavily loaded (the overall consumption is low), no congestions occur and a minimum-cost dispatch of the generators can be reached. Thus, no large difference in total generation costs can be observed among the different studied cases. As a result, FACTS devices offer a small benefit in such a case. The effect of FACTS devices becomes more evident in higher loadings, especially exceeding 80% of the maximum value. With more FACTS devices installed, the benefit with respect to the generation costs increases.

It should also be noted that the contribution of shunt controllable devices is significantly smaller than of series-connected FACTS. This is due to the load characteristics as well as to the inherent characteristics of the devices. Shunt

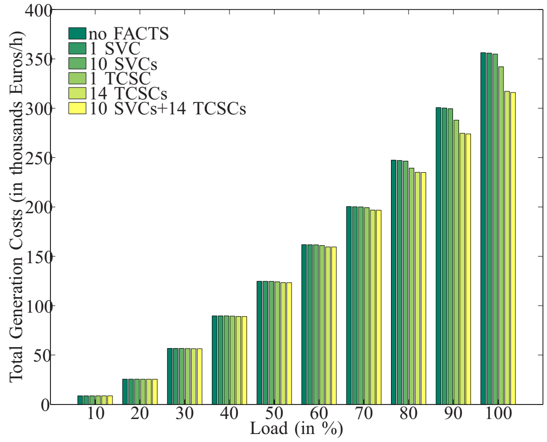

Fig. 3: FACTS contribution on different consumption levels (SC-OPF).

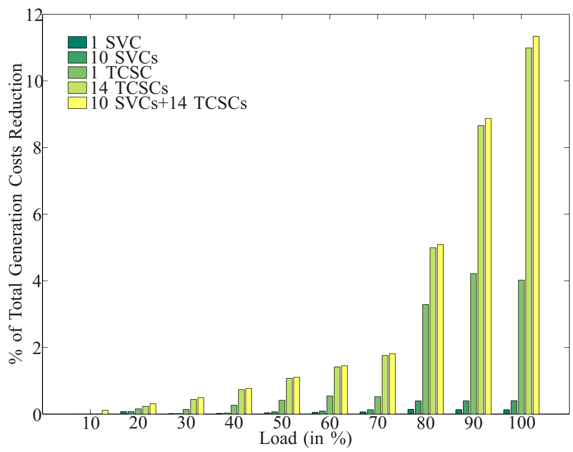

Fig. 4: FACTS contribution on different consumption levels (SC-OPF) (percentage difference from the base case: No FACTS, SC-OPF).

FACTS are expected to contribute to the voltage profile of the system and also correct the power factor of the connected loads. In our system, all loads are assumed to have a power factor of 0.95 inductive, a value which is close to unity. In case a lower power factor had been assumed, the contribution of shunt FACTS would have been more apparent. A single SVC device has, nevertheless, been observed to perform marginally better than a TCSC during a 10% consumption level and a standard AC-OPF.

C. Comparison of Generator Costs with Standard OPF and SC-OPF

In this part, the economic dispatch of the generators is compared when the system is in a N-0 state (standard OPF) and when it is in a N-1 secure state (SC-OPF). The consumption level is assumed to be 100% in all cases. In Fig. 5, the green line represents the generator dispatch when the system is in a N-1 secure state. With no FACTS installed, the SC-OPF results in significantly higher costs compared with a situation where a standard AC-OPF is solved. In practice, the solution of the SC-OPF should be implemented, since the system must be N-1 secure. The increase in comparison with the AC-OPF represents the "cost of security" and amounts to about 9.2% as shown in Fig. 6. With the installation of FACTS, it can be observed that both the AC-OPF and the SC-OPF result in lower costs. However, the difference in generation costs between the N-0 and the N-1 case decreases when installing FACTS devices. The installation of a single TCSC results in only 6.2% higher costs than in the N-0 secure state, where also a series FACTS has been installed. The "cost of security" is almost zero in case a series FACTS device is installed in more than three lines of the system.

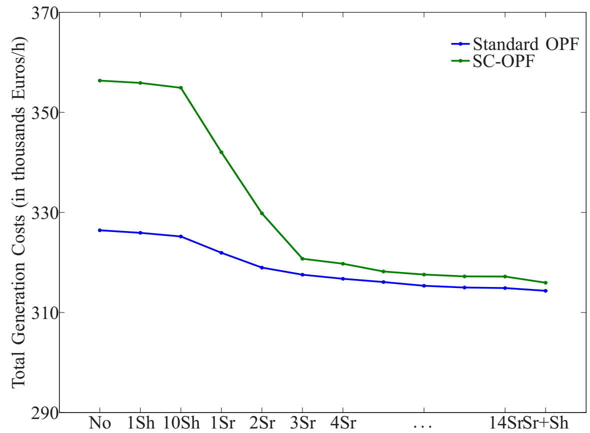

Fig. 5: Effects of FACTS devices in the generation costs, when no security criteria are considered (standard OPF) and when the N-1 security criterion is incorporated (SC-OPF). [1Sh:1 SVC; 3Sr:3 TCSCs; Sr+Sh:10 SVCs and 14 TCSCs]

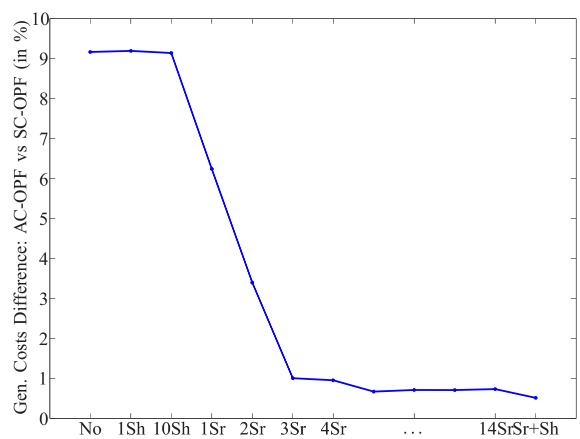

Fig. 6: Difference in Generation Costs between a standard OPF and an SC-OPF, when different FACTS devices are installed.[1Sh:1 SVC; 3Sr:3 TCSCs; Sr+Sh:10 SVCs and 14 TCSCs]

Based on the results shown in Fig. 5 and Fig. 6, it can be concluded that installing series FACTS devices relieves congestions and allows a power system to operate in a N-1 secure state, achieving at the same time a generation dispatch similar to the case where FACTS are installed but no security criteria are considered. In other words, the installation of FACTS devices enables the system to operate with the optimal economic dispatch and minimizes the "cost of security" to zero. When an outage occurs, FACTS offer the flexibility (by changing instantaneously the line reactances) to bring the system into a secure state and avoid line overloadings. A further observation at this point is that the installation of more than three TCSCs does not result in significant additional cost savings for the system.

V. FACTS vs. Line Upgrade

A question that emerges when network reinforcements are addressed is whether a FACTS device should be installed or a new line should be built. In this section, we study the effect a new line would have on the generation costs and we compare its performance with a single TCSC installation. The TCSC is assumed to be installed in line $6-7$. Line $2-10$ is selected to be upgraded and its capacity is doubled[3]. An SC-OPF has been solved for the base case (100% consumption level) and has been compared with the installation of 1 TCSC or a line upgrade. The loadings of each line for the three different cases are presented in Fig. 7.

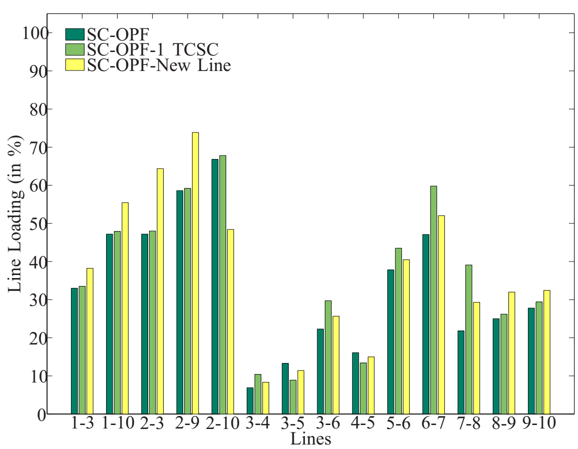

Fig. 7: Line Loadings. Comparison between the base case, adding a TCSC or reinforcing a line.

In Fig. 8, the total generation costs for all three cases and for different consumption levels are illustrated. Fig. 9, showing the percental reduction in generation costs, is more helpful for our assessment. A TCSC is already effective from a consumption level of about 20%. A more economic dispatch of the generators can be achieved, although the cost reduction is small. A line upgrade, on the other hand, has no effect on lower consumption levels. But in high loads, it outperforms the TCSC in terms of generation costs. As it is shown, until a consumption level of about 80% a FACTS device is more efficient, but in case of a 90% or 100% system loading, a line upgrade can offer significant benefits. In a dilemma "FACTS or new line" the question to be asked is: how loaded is usually the system? If the system is for a significant amount of time loaded near its limits, a line upgrade is recommended. If not, the system would benefit more from a FACTS installation.

[3]Line $2-10$ is very often congested. From an assessment we carried out, the upgrade of line $2-10$ would lead to a more economic dispatch than any other line upgrade.

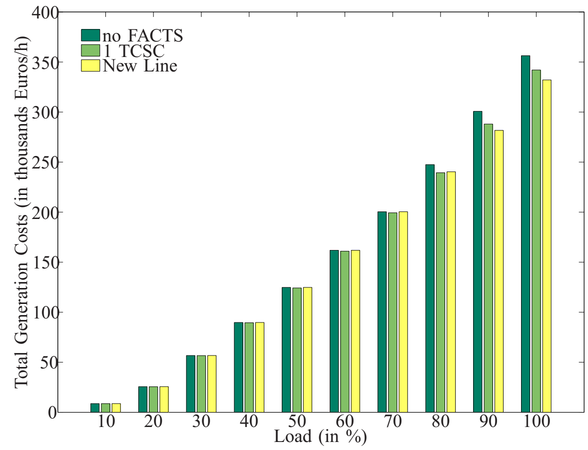

Fig. 8: Total Generation Costs for different consumption levels (SC-OPF). [Base Case; Adding a TCSC; Reinforcing a Line]

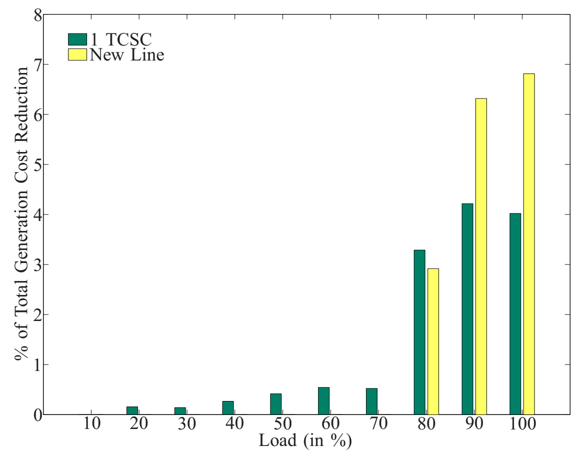

Fig. 9: Reduction of total generator costs (in %) with respect to the base case SC-OPF. Comparison between TCSC installation and Line Reinforcement.

VI. TCSC Device vs. Line Upgrade for Realistic Load Profiles

The previous sections focussed on rather theoretical comparisons of different FACTS devices and a line upgrade, dependent on different loading levels of the system. This last case study aims again at comparing the installation of a TCSC device with a line upgrade, but this time we assume realistic load profiles. We took four typical days of the year, one for each season. The data for the load curves were extracted from real load curves of Switzerland [11], where we converted the data into per unit values (maximum loading = 100%). The load profiles are displayed in Fig. 10. For the analysis always a security-constrained OPF has been run, as the system in reality is supposed to normally operate in an N-1 secure state.

Concerning the placement of the TCSC device, we chose the line connecting nodes 6 and 7 as this location has the strongest influence in terms of a reduction of total generation costs. Nonetheless, the transmission capacity was upgraded (doubled) on the line connecting nodes 2 and 10. On this line, congestion occurs most frequently. From an optimal placement

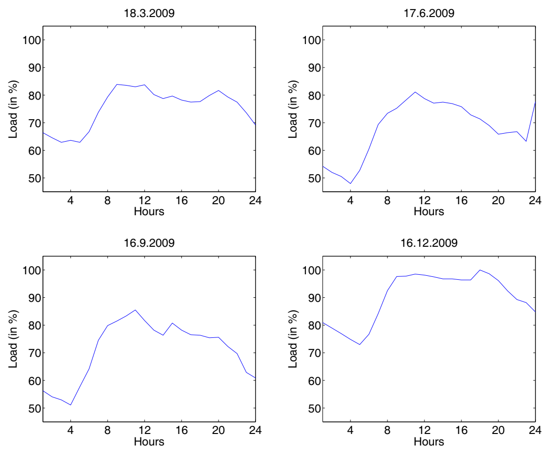

Fig. 10: Load profiles of four typical days for Switzerland.

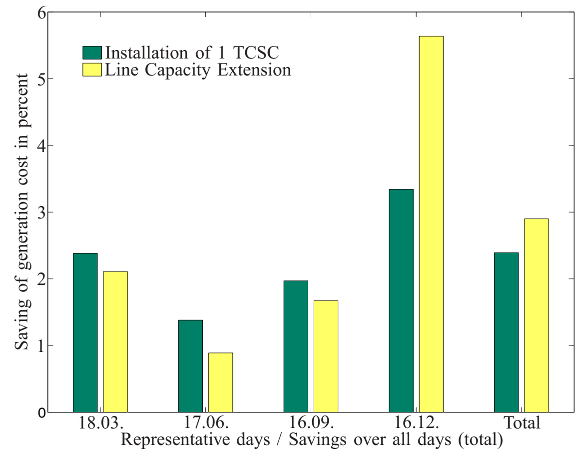

Fig. 11: Savings in total generation cost in percent for a) TCSC installation in line 6-7 and b) doubled transmission capacity of line 2-10, in comparison with the base scenario. Position 'Total' represents accumulated savings over all days.

perspective this result appears interesting as it suggests that the optimal location for reinforcing the network does not necessarily coincide with the 'weak' (the congested) network point itself but is dependent on the choice of technology.

Fig. 11 shows the savings in generation costs (in percent) per each representative day considering either the installation of a TCSC device or a line upgrade. During spring (18.03.), summer (17.06.), and fall (16.09.) the savings resulting from a TCSC device are slightly higher than from the line upgrade. However, in winter (16.12.) the line upgrade "outperforms" the TCSC device. The difference in savings amounts to approximmately 3%. Obviously, the TCSC device performs economically better in low loading conditions (not exceeding 80% of the peak load), whereas at peak load the line upgrade leads to lower overall generation costs. This behavior has already been described in the previous section. In total (sum over all representative days), the line upgrade leads to slightly higher savings compared with the TCSC device. The results for our test network suggest that a TCSC might be the appropriate choice for temporary congestions, whereas a line upgrade is indicated in case of permanent congestion on specific lines.

Attempting to investigate the relationship between the generation cost savings and the investment costs, we calculated a monetary indicator, as mentioned in Section III. The TCSC in the specific study has a power rating of 2300 MVAr[4] and with a cost of 50k€/MVAr (see [6], p.94), the total investment costs are 115M€. This results to 0.42 Euros annually saved per invested Euro. For an overhead line of 150 km length with costs of 0.8 M€/km [12], the investment cost is 120M€. This results to 0.49 Euros annually saved per invested Euro. As it can be observed, the investment in a new line seems slightly more cost effective in this case. Nevertheless, before the final investment decision other factors should also be considered, such as the right-of-way costs for the overhead line, environmental impacts and the licensing procedures.

[4]Note that the case study is performed on an equivalent aggregated system. The specified power rating could be achieved by installing more than a single TCSC.

VII. Conclusions and Outlook

This paper presented a novel formulation of a security-constrained optimal power flow. The formulation is based on a "full" AC optimal power flow, where system security has been incorporated using linear sensitivities, such as Power Transfer Distribution Factors (PTDFs), Line Outage Distribution Factors (LODFs) and Generalized Generation Distribution Factors (GGDFs). A comparison between a standard OPF and the SC-OPF solution allows to calculate the "cost of security". In conjunction with the OPF formulation, a valuation framework for assessing different types of FACTS as well as line upgrades has been introduced. This framework considers indicators, such as total generation costs, the overall loading of the system and the loading of individual lines (congestion). Complementary studies quantified the inclusion of system security in the OPF formulation and the effects of different consumption levels. The applicability of the framework has been proven for a test network. Results on this network suggest the following:

- With FACTS devices the system can operate in a N-1 secure state, but close to an economic dispatch obtained for the N-0 security situation. In other words, the "cost of security" because of redispatching decreases to zero.
- A TCSC device performs economically better in low loading conditions (not exceeding 80% of the peak load), whereas at peak load a transmission line upgrade leads to lower overall generation costs. Thus, for the test network a TCSC was the appropriate choice for temporary congestions, whereas a line upgrade was indicated in case of permanent congestion on a specific line.
- From an optimal placement perspective the optimal location for reinforcing the network does not necessarily coincide with the 'weak' (the congested) network point itself but is dependent on the choice of technology. The line upgrade proved to be economically most efficient on the congested line itself. However, the installation of

a TCSC led to a stronger reduction in generation costs when placed on a line different from the congested one.
- The installation of more than a limited number of TCSCs did not result in significant additional cost savings for the system studied in this paper.

The framework proposed in this paper attempts to provide an insight of how a FACTS device or a line upgrade would influence system security and total costs. However, for an investment decision additional factors need to be taken into account. For example, the costs for the line reinforcement depend on the line length, while the FACTS costs depend usually on their power rating. A line upgrade increases significantly the security margin of the system by adding new transfer capacity. However, the right-of-way costs, the environmental impacts and the long licensing procedures in order to build a new transmission line must be taken into account. Additional advantages of FACTS devices, e.g. damping oscillations during transient phenomena can also be considered.

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APPENDIX

TABLE II: Generator and Loads

# bus	P_{load} [MW]	Q_{load} [MVAr]	P_{gen} [MW]	a_1 [Eur/MW]	a_2 [Eur/MW^2]
1	55	18	–	–	–
2	55	18	1200	6.9	0.00067
3	1300	427	8000	24.3	0.00040
4	650	214	–	–	–
5	650	214	3000	29.1	0.00006
6	200	66	–	–	–
7	2600	855	800	6.9	0.00026
8	3600	1183	2000	50.0	0.00150
9	1100	362	–	–	–
10	1900	624	–	–	–

TABLE III: Transmission line parameters [S_{base}=1000 MVA]

from # bus	to # bus	R [p.u.]	X [p.u.]	B [p.u.]	S_{ij}^{max} [MVA]
1	3	0.04	0.10	0.04	4200
1	10	0.08	0.27	0.08	2800
2	3	0.01	0.12	0.01	4900
2	9	0.02	0.07	0.02	3164
2	10	0.02	0.14	0.02	2212
3	4	0.02	0.10	0.02	2492
3	5	0.02	0.17	0.02	3010
3	6	0.02	0.17	0.02	4900
4	5	0.02	0.17	0.02	3010
5	6	0.02	0.17	0.02	3920
6	7	0.01	0.16	0.01	4900
7	8	0.01	0.25	0.01	2800
8	9	0.01	0.25	0.01	3164
8	10	0.04	0.07	0.04	4900

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