Real Option Valuation of FACTS Investments Based on the Least Square Monte Carlo Method

Gerardo Blanco, *Graduate Student Member, IEEE*, Fernando Olsina, Francisco Garcés, and Christian Rehtanz, *Senior Member, IEEE*

***Abstract*—Efficient and well-timed investments in electric transmission networks that cope with the large ongoing power market uncertainties are currently an open issue of significant research interest. Strategic flexibility for seizing opportunities and cutting losses contingent upon an unfavorable unfolding of the long-term uncertainties is an attribute of enormous value when assessing irreversible investments. In this sense, flexible AC transmission systems (FACTS) devices appear as an effective manner of adding flexibility to the transmission expansion planning. This article proposes an investment valuation approach which properly assesses the option value of deferring transmission lines investments whereas gaining flexibility by investing in FACTS devices. The flexibility provided by FACTS investments—option to abandon and to relocate—is assessed through a real option valuation approach based on the novel least square Monte Carlo method. In order to illustrate the practicability of the proposed valuation approach, a traditional expansion strategy (lines) and a flexible investment strategy (lines and FACTS) are compared in a real study case. The article shows that a proper combination of lines and FACTS leads to efficient investments by allowing a progressive adaptation of the transmission grid to the changing scenarios.**

***Index Terms*—Dynamic programming, flexibility, risk analysis, stochastic simulation, transmission planning, uncertainty.**

I. Introduction

THE transition towards a competitive electricity sector has increased the requirement for efficient operation and planning of the transmission network to enhance the degree of market competition. Efficient allocation of transmission investments and timely expansion decisions are therefore becoming increasingly important.

Several algorithms and approaches have been proposed for solving this complex problem [1]. Nevertheless, the theory and tools for assessing transmission investments (TIs) are still below the practical requirements of the new power markets. This is particularly true in aspects such as the TI flexibility and the introduction of transmission controllers.

The inevitable long-term uncertainties involved in the transmission expansion planning are better coped with flexible investments. Planners need flexibility for seizing opportunities or avoiding losses upon the occurrence of unfavorable scenarios. This flexibility may include various actions at different stages of the investment horizon, such as the options to defer, expand, or even abandon the project. In this context, flexibility has a substantial value, and must be taken into consideration within the decision-making process.

Usually, grid reinforcements are primarily focused on investments in new transmission lines (TL). This kind of TI has a huge level of irreversibility, which leads to a high risk exposure to the long-term uncertainties. In addition, expanding the grid in this conventional manner might not be the best way to deal with some constraints, especially those that arise due to the lack of control over power flows [2].

An alternative for dealing with these shortcomings is the installation of flexible AC transmission systems (FACTS), instead of building TLs. FACTS are power electronics-based devices for the control of voltages and/or currents, which enhance controllability and the power transfer.

The original objective has been to use FACTS controllers to operate near the safety margins set up according to the transient stability, and consequently, the power flow through the existing transmission lines can be raised near to their thermal limits [3]. Hence, it would be possible to defer the financial investment needed to build new lines [4].

In addition, FACTS investments exhibit features that considerably improve their flexibility, e.g., modularity and higher reversibility. Thus, the inclusion of FACTS in the TI portfolios adds new strategic options to the grid expansion plan that significantly improves its flexibility.

Some contributions have recently been made in this area. These works show that expansion alternatives with FACTS present similar performance compared to traditional network upgrading [2]–[6]. However, all these papers apply the net present value (NPV) method and consider neither the uncertainty on future market conditions nor the flexibility value added by the FACTS to the network planning.

Since installation of FACTS devices requires substantial expenditures, all benefits that these devices provide must be assessed. For instance, a fact often ignored is the ability of relocating or selling out these devices at a substantial value. This flexibility is relevant in order to make optimal TI decisions and should consequently be fairly valued. Any attempt at valuing

Manuscript received March 03, 2010; revised April 09, 2010, July 14, 2010, and November 07, 2010; accepted November 12, 2010. Date of publication January 06, 2011; date of current version July 22, 2011. This work was supported in part by the German Academic Exchange Service (DAAD), the Argentinean Research Council (CONICET) and in part by the Argentinean Agency for Promotion of Science & Technology (ANPCyT). Paper no. TPWRS-00168-2010.

G. Blanco is with the Facultad Politécnica at Universidad Nacional de Asunción (UNA), University City, San Lorenzo, Paraguay (e-mail: gblanco@pol.una.py).

F. Olsina and F. Garcés are with the Institute of Electrical Energy (IEE), National University of San Juan (UNSJ), San Juan 5402, Argentina (e-mail: olsina@iee.unsj.edu.ar; garces@iee.unsj.edu.ar).

C. Rehtanz is with the Institute for Power Systems and Power Economics, Technische Universität Dortmund, 44221 Dortmund, Germany (e-mail: christian.rehtanz@tu-dortmund.de).

Digital Object Identifier 10.1109/TPWRS.2010.2094211

flexibility almost naturally leads to the notion of real options (ROs) [7].

The RO valuation (ROV) technique provides a well-founded framework—based on the financial options theory—to assess investments under uncertainty. It quantitatively takes into account the risks and the flexibility value for making decisions contingent to unfolding information.

RO models often exhibit higher complexity than the financial options. Indeed, real projects exhibit an intricate set of interacting options, complicating their evaluation.

In this sense, Longstaff *et al.* [8] proposed a method for solving interacting financial options, based on Monte Carlo simulations. Recently, Gamba [9] exposed an extension of this approach for valuing capital investment problems with embedded options considering the interaction and interdependence among them.

Although option pricing approaches based on simulation methods have already been used in the fields of finance and economics [10], [11], even including the evaluation of generation investments [12], [13], it is the first time that the usefulness of these techniques has been proved for assessing FACTS projects in particular, and for power transmission investments in general.

This paper is an extension of the research presented in [14] and illustrates the applicability of this approach to the TI problem with several embedded ROs. The approach considers FACTS as a TI alternative, appropriately valuing the flexibility of relocating and abandoning them as well as the deferral option on both FACTS and TL projects.

II. Flexibility in Transmission System Investments

In grid expansion studies, network upgrades are decided by either motivations to reduce system operational costs due to transmission congestions or by network reliability or security requirements [2].

The TI valuation problem should be formulated taking into account the nature of the investment involved. Scale economies, low adaptability, lumpiness, irreversibility, and deferral options are typical TI characteristics [15].

Due to the significant economies of scale, transmission expansions meet the load growth by infrequently investing in large transmission projects with low adaptability [15].

Moreover, TIs, once executed, are considered irreversible. In fact, it is very unlikely this equipment can serve different purposes if conditions turn out to be adverse [14].

Consequently, the valuation of TIs should be treated as a risk management problem, in which flexible investments act as a hedge against adverse scenarios. In case of unfavorable conditions, this flexible investment should let the planner adjust, making changes in an easy and economical way [16].

Typically, TI projects are not now-or-never opportunities. Hence, the postponement option of the investment decision is one of the most relevant flexible features of traditional transmission expansions. Indeed, keeping the investment option open waiting for uncertainties being partially resolved is the main hedge against an adverse evolution of the future. Thus, the time for optimally exercising the investment option is a key factor determining the efficiency of the expansion. Accordingly, network investments should be treated in an analogous way to an American call option [17]. In fact, the opportunity cost incurred when the ability of deferring is lost must be assessed together with other costs and benefits.

In most cases, the substantial value of the postponement option and the lumpiness of the transmission projects lead to retain flexibility by delaying the TI decision. Normally, this entails a waiting period of several years until the grid is effectively upgraded. Accordingly, it is imperative to seek new flexible TI alternatives, which combined with conventional expansion projects diversify the TI portfolio, allowing a more efficient management of uncertainties.

In this context, as was mentioned before, FACTS devices seems to be a suitable alternative for increasing the flexibility of the TI portfolios (TIPs).

The several benefits offered by FACTS in the liberalized markets are currently under intensive research. A review of the literature in the field shows that FACTS have a major influence on many aspects of power market behavior. In numerous papers, the impact of FACTS on congestion management is analyzed, as well as their ability to improve controllability and reliability of power systems [6].

Despite the many advantages offered by FACTS devices, there are only few proposals [2]–[6] for integrating them into the network expansion planning. Valuing in monetary terms the gained flexibility in transmission expansion plans by investing in FACTS—while postponing conventional transmission projects—is a key issue that still remains uninvestigated. The main flexibility options provided by FACTS are analyzed in the following.

A. Abandon Option

According to the typical cost structure of FACTS investments, power electronic components represent about 50% of the total cost [18]. Accordingly, the scrap value of the FACTS devices should be considerable.

Recently, in a previous article from the authors [14], the authors highlighted the importance of the strategic option to resell the devices in the future if complementary investments have been executed (i.e., TLs) or the evolution of the power market uncertainties unfolds unfavorably. This article extends that approach, by including the relocation option.

B. Relocation Option

As pointed out in [6], new FACTS designs allow installation so that they can easily be relocated: e.g., power electronics and auxiliary components are installed in a movable container, whereas high voltage equipment is installed fixed on-site. This novel feature opens the option to relocate the device according to the development of system uncertainties. This paper proposes a methodology to quantify in economic terms the value of this option.

III. Valuing Flexible Investment Under Uncertainty

It has been proven that the traditional NPV valuation can be misleading for appraising irreversible investments under uncertainty in the presence of managerial flexibility [19].

The RO approach is an investment valuation technique suitable for flexible projects subject to uncertainty, which applies notions from finance theory to the valuation of capital investments. It refers to choices on whether and how to proceed with investment projects. This appraisal provides a decision-making tool for investments that might be delayed, expanded, abandoned, or repositioned.

In the first RO applications, valuation was normally confined to the investment options that can be easily assimilated to financial options, for which solutions are well-known and readily available [11]. This was done using few underlying assets and simple options with European features or American perpetual options [10]. Nevertheless, an investor normally is confronted with a large and diverse set of opportunities. From this point of view, investment projects can be seen as a portfolio of options [17], where its value is frequently driven by several stochastic variables.

The introduction of multiple interacting options into RO models highly increases the problem complexity, making traditional numerical approaches impracticable. However in the recent years, simulation procedures for solving multiple options have been successfully proposed. One of the most powerful approaches is the least square Monte Carlo (LSM) method proposed by Longstaff and Schwartz [8]. LSM method is based on stochastic chronological simulation and uses least squares regression to determine the optimal stopping time in the decision-making process.

The main contribution of this work is presenting an LSM-based method for evaluating the complex RO problem involved in TIs, including the FACTS-related options.

A. Least Square Monte Carlo Valuation Framework

The value of an American option, with state variable X_τ, payoff $\Pi(\tau, X_\tau)$, where Π is a known profit function, and that can be exercised from t until maturity T, is equal to

$$F(t, X_\tau) = \max_{\tau \in T} \left\{ \mathbb{E}_t^* \left[\Pi(\tau, X_\tau) \cdot (1+\rho)^{-(\tau - t)} \right] \right\} \quad (1)$$

where τ is the optimal stopping time ($\tau \in [t, T]$) and the operator $\mathbb{E}_t^*[.]$ represents the expectation conditional on the information set available at t. The discount factor between any two periods is $df = (1+\rho)^{-1}$, where ρ is the adjusted-risk discount rate.

The LSM approach proposed a Monte Carlo simulation algorithm to estimate the option value stated in (1) [10]. Equation (1) can be expressed in a discrete time splitting the maturity time T in N discrete intervals. Then Ω sample paths of the underlying asset are generated by means of Monte Carlo simulation techniques.

The optimal stopping policy—along the path ω—can be derived by applying the Bellman's principle of optimality: "*An optimal policy has the property that, whatever the initial action, the remaining choices constitute an optimal policy with respect to the sub-problem starting at the state that results from the initial action*" [19]. This statement can mathematically be expressed as follows:

$$F(t_n, X_{t_n}) = \max\left\{ \Pi(t_n, X_{t_n}), \mathbb{E}_{t_n}^* \left[F(t_{n+1}, X_{t_{n+1}}) \right] \cdot df \right\}. \quad (2)$$

By this equation, we can determine the optimal path policy, by comparing the continuation value

$$\Phi(t_n, X_{t_n}(\omega)) = \mathbb{E}_{t_n}^* \left[F(t_{n+1}, X_{t_{n+1}}(\omega)) \right] \cdot df \quad (3)$$

with the payoff $\Pi(t_n, X_{t_n})$. Hence, the optimal stopping time for the ωth realization is found, beginning at T and working backwards, by applying the following condition:

$$\text{if } \Phi(t_n, X_{t_n}(\omega)) \leq \Pi(t_n, X_{t_n}(\omega)) \text{ then } \tau(\omega) = t_n. \quad (4)$$

At maturity, the options are no longer available. Therefore, the continuation value equals zero, $\Phi(T, X_T) = 0$, consequently (4) holds as long as the payoff value is positive. Prior to T at t_n, the option holder must compare the payoff obtained from the immediate exercise, $\Pi(t_n, X_{t_n}(\omega))$, with the continuation value, $\Phi(t_n, X_{t_n}(\omega))$. When the decision rule (4) holds, the stopping time $\tau(\omega) = t_n$ is updated. Finally, the value of the option is then calculated as the mean of the values over all samples [7]:

$$F(0, x) = \frac{1}{\Omega} \sum_{w=1}^{\Omega} \Pi\left(\tau(\omega), X_{\tau(\omega)}\right) \cdot (1+\rho)^{-\tau(\omega)}. \quad (5)$$

Then, the problem reduces to one of finding the expected continuation value at (t, X_t), in order to apply the rule (4). Here, the LSM method estimates the continuation for all previous time-stages by regressing from the discounted future option values on a linear combination of functional forms of current state variables. Considering that the functional forms are not evident, the most common implementation of the method is simple powers of the state variable (monomial) [8]–[10].

As exposed in [11], let us define L_j, with $j = 1, 2, \ldots, J$ as the orthonormal basis of the state variable X_t used as regressors to explicate the occurred present value in the ωth realization, then the least square regression is equivalent to solve the following optimization problem:

$$\min_{\varphi} \sum_{w=1}^{\Omega} \left[\Pi\left(t_{n+1}, X_{t_{n+1}}(\omega)\right) \cdot df - \sum_{j=1}^{J} \varphi_j L_j(X_{t_n}(\omega)) \right]^2. \quad (6)$$

Then the resulting optimal coefficients φ^* from solving (6) are utilized to estimate the expected continuation value $\Phi^*(t_n, X_t(\omega))$ applying the following expression:

$$\Phi^*(t_n, X_t(\omega)) = \sum_{j=1}^{J} \varphi_j^* L_j(X_{t_n}(\omega)). \quad (7)$$

Working backwards until $t = t_0$, the optimal decision policy on each sample path—choosing the largest between the immediate exercise and the expected continuation value—can be determined. Finally, by applying (5), the value of the American option can be computed.

In order to clarify the applied optimization procedure, a flow chart diagram is shown (Fig. 1) which portrays the evaluation procedure of a deferral option of maturity equals to two years by the LSM method, looking forward to add clearness to the concept this appraisal. In this figure, $PV_{k,i}$ is the present value

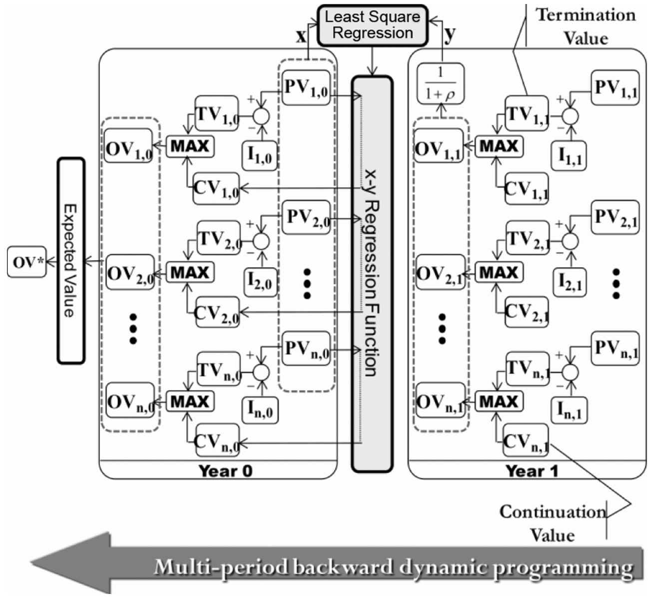

Fig. 1. Deferral option valuation by the LSM method.

and $OV_{k,i}$ is the option value of the investment alternative at the simulation path k and the year i. Likewise, $TV_{k,i}$ is the termination value, $CV_{k,i}$ is the continuation value, and ρ represents the risk-adjusted discount factor.

In this case, the optimal policy of exercising the options is derived by comparing the intrinsic value of the deferral option with the value of keeping alive the option using backward dynamic programming techniques. The problem starts from the latest year—where the continuation value is zero—and working backward is completed in the first year. Although the above chart flow diagram focuses on a single deferral option, the proposed approach optimizes multiple options, i.e., deferral, abandon, and relocation options.

B. Multi-Option Investment Problems

In [9], Gamba has presented an extension of the LSM method to value independent, compound, and mutually exclusive options. According to that approach, options can be classified as [10] follows.

Independent options: The value of a portfolio comprising only independent options is equal to the sum of each individual option value, computed by the LSM method. Only in this situation, the additivity property holds, even when the underlying assets might be not independent.

Compound options: Let a portfolio of H compounded options, where the execution of the hth option creates the right to exercise the subsequent $(h+1)$th option. A typical example of this kind of sequential option is the right to expand capacity, which is just originated when the initial investment option is exercised.

Mutually exclusive options: A set of options are mutually exclusive when the exercise of one of them eliminates the opportunity of execution of the remainder. The expansion and abandon options are common examples of mutually exclusive options. Thus, the problem is extended to find both the optimal stopping time and optimal option to be exercised. Therefore, the variable control is a bi-dimensional variable, τ and ζ; where τ is an exercising time in $[t, T_h]$ and $\zeta \in \{1, 2, \ldots, H\}$.

The mathematical formulation for the appraisal of these multiple options is presented in detail in [9].

IV. Valuation of Flexible TIPs Including FACTS

Let us consider a power market where the transmission network is operated by an independent system operator which submits a transmission expansion plan in order to be evaluated by the regulatory agency.

The valuation of this TI plan is the focus of this paper. The reduction of the system costs incurred for serving the forecasted load demand over the optimization horizon is used as the measure to evaluate the economic performance of the proposed network upgrades.

Hence, the value of a TIP will be defined by the variation of the social welfare resulting from executing the investments considered in the portfolio. The incremental social welfare should be quantified through the cost savings between the base (without TI) and the investment scenarios.

The optimization process for the optimal location of FACTS devices is beyond the scope of this paper. This article is focused on appraising a feasible set of transmission investments portfolios. Thus, once an investment alternative fulfills the legal requirements, i.e., the building license, right-of-way, environment permission, service leasing, etc., it is considered as feasible. Then, only the feasible TIPs are assessed by the proposed approach.

This article proposes an extension of the model published in [14], considering the relocation and the abandon option when investing in FACTS, as well as a more detailed FACTS device model. In the following, the mathematical algorithms for assessing the performance of TIPs including FACTS devices under long-term uncertainties are presented.

A. Stochastic Simulation of the Power Market Operation

In this module, the stochastic behavior of the power market over the study horizon is simulated through the Monte Carlo method. The stochastic behavior of the main uncertain input variables is modeled by appropriate random processes, which are described in the following.

Demand growth rate: the evolution of the electricity demand is a key variable largely influencing the performance of TIs.

For the sake of simplicity, only two demand periods (base and peak) are taken into account, and the period durations are assumed constant during the evaluation. The uncertain evolution of the load demand on each geographical area is modeled as a stochastic growth rate. The zonal demand growth rate is replicated through a multivariate stochastic process, illustrated below, which suitably considers the correlation between geographic areas of the system [20]:

$$dR^j(t) = \mu_{R^j}(t) \cdot dt + \Theta \cdot dW$$
$$R^j(t) = \begin{bmatrix} R^j_{1,p}(t) & R^j_{1,b}(t) \\ \vdots & \vdots \\ R^j_{n,p}(t) & R^j_{n,b}(t) \end{bmatrix} \quad (8)$$

where $R^j(t)$ is the matrix of stochastic growth rates at the time t and jth realization, $R^j_{n,p}(t)$ and $R^j_{n,b}(t)$ growth rates in peak demand and base of the nth node, at the instant t in the jth realization, respectively. $\mu_{R^j}(t)$ represents the vector drift at time t. Hereafter, the vector of the Wiener process in t of the jth realization is denoted by dW. Θ is an $n \times n$ lower triangular matrix satisfying $\Upsilon = \Theta.\Theta$, where Υ is given by $n \times n$ covariance matrix, defined by $\Upsilon = \Psi.\Gamma.\Psi^t$. The diagonal matrix of variances is defined according to $\Psi(i,i) = \sigma^2(i)$ (the variance of zone i), and the matrix of correlations between areas according to $\Gamma(i,j) = \rho_{i,j}$ (the correlation between areas i and j).

Generation costs: The generation costs typically include fuel, O&M, and startup costs. Commonly, generation cost is linked to the fuel prices through the heat curve of the generating unit, according to the following expression [21]:

$$C\left(q(t), p_F(t)\right) = a_0 + a_1 \cdot q(t) + a_2 \cdot q(t)^2 \tag{9}$$

where $C\left(q(t), p_F(t)\right)$ is the generation cost at a production level $q(t)$ in [MW] and $p_F(t)$ is the fuel price in [€/MWh]. Hence, the uncertainty on the generation cost in thermal units is strongly linked to fuel price variations. It is quite common to model the stochastic dynamics of fuel price fluctuations as a mean reversion stochastic process. Instead of formulating the mean-reversion model in the prices themselves, it is formulated in the logarithms of prices [21]:

$$d\left(\ln p_F(t)\right) = \alpha \cdot \left(\ln \overline{p_F} - \ln p_F(t)\right) + \sigma^{\ln p^F} \cdot dW \tag{10}$$

where α is the speed of reversion to the mean, $\sigma^{\ln p^F}$ is the volatility of natural logarithmic of prices, and $\overline{p_F}$ is the "reversion level" of fuel prices.

Subsequently, with the demand growth and fuel price simulations as inputs, optimal power flow calculations are conducted in order to determine the minimal operation cost of each hour of the investment horizon under the base and the investment scenario. A DC representation of the network is considered in the OPF model. The cost difference between both scenarios defines the underlying asset (incremental social welfare), which is assessed later on.

The DC-OPF is calculated using the MATLAB-based power system simulation package Matpower 3.2 [22], modified to introduce FACTS devices in the transmission system (TS). These FACTS are implemented according to the mathematical model which is described below.

Electrical model of the FACTS: In this article, a thyristor controlled series compensator (TCSC) is considered. It was chosen given that it is most suitable for dynamically controlling power flows in an electric power system under rather unpredictable changing conditions. In comparison to more conventional compensation strategies (e.g., fixed series compensation), it has the advantage of a very fast output response to changes in control values. Indeed, since this work analyzes the power market operation under uncertainty and the flexibility of the TIs, a continuous, dynamic and flexible compensation according to the unfolding of the uncertain variables is required.

The TCSC mathematical model is developed based on its steady-state operation. By modifying the TL reactance, the TCSC acts as a capacitive/inductive compensator. Its rating depends on the reactance and maximal current that can flow through the TL where it is located:

$$b_{ij} = \frac{1}{X_{Line} + X_{TCSC}}; \; X_{TCSC} = r_{TCSC} \cdot X_{Line} \tag{11}$$

where X_{Line} is the reactance of the TL and r_{TCSC} is the coefficient which defines the compensation degree by the TCSC X_{TCSC} [23]. Based on the DC power flow model, the power flow along the line $i - j$ with a TCSC can be formulated as

$$P_{ij} = b_{ij} \cdot (\theta_i - \theta_j). \tag{12}$$

The representation of the FACTS applied in this paper is based on the power injection model (PIM), which results by interpreting the power injections of the converters as real and reactive node injections. Through PIM, FACTS devices can be included into power flow formulation without any alteration of the admittance and the Jacobian matrixes [23].

The power injections are formulated according to the type of FACTS modeled. For a TCSC connected between the nodes i and j, the power injection can be derived as

$$P_{F,i} = -P_{F,j} = \frac{X_{TCSC}}{X_{ij} \cdot (X_{ij} - X_{TCSC})} \cdot (\theta_i - \theta_j). \tag{13}$$

Within the classic DC-OPF problem, power injections related to FACTS devices must be added to nodal power balance constraints. In addition, the constraints related to the line power transfer limits in the compensated branches must be modified. The transfer capacity in the compensated line is increased by 12% due to the stability improvement [6].

To avoid overcompensation, the operating range of the TCSC is chosen between $-0.7\, X_{Line}$ and $0.2\, X_{Line}$ [6]. Due to the fact that TCSC power injections are a function of voltage angles as well, which are state variables in DC-OPF model, there are no fixed limits for these power injections, but there are fixed limits for X_{TCSC}. Therefore, operating constraints of the TCSC are two extra inequality constraints:

$$P_{F,i} + \frac{X_{TCSC}^{\max}}{X_{ij} \cdot (X_{ij} - X_{TCSC}^{\max})} \geq 0 \tag{14}$$

$$P_{F,i} + \frac{X_{TCSC}^{\min}}{X_{ij} \cdot (X_{ij} - X_{TCSC}^{\min})} \leq 0. \tag{15}$$

In [14], the mathematical model of FACTS is developed by modifying the reactance of the transmission line. The TCSC acts as the capacitive or inductive compensation, respectively. In this study, the reactance of the transmission line is adjusted by TCSC directly. This model implies a bi-level optimization approach, where the DC-OPF optimization problem is embedded into the optimal TCSC reactance setting problem. The main drawback of this approach is the huge computation time required to perform thousands optimizations within the Monte Carlo simulation. Additionally, the study case in [14] analyzed investments in a small three-bus system, and does not assess the option to relocate the FACTS controller. The application of this approach is unfeasible for large power system and it is necessary to look for alternative formulation to this problem. In this context, the PIM model allows us to conduct the overall optimization problem in an integrated process, significantly reducing the computation effort with the same level of accuracy.

B. Financial Assessment of TIPs

This module estimates the present value of the incremental social welfare (ISW) cumulated on the study horizon on the basis of the system cost savings.

First, the cash flows of the ISW originated by the execution of the proposed TIP are discounted by the weighted average cost of capital (WACC):

$$PV\left(ISW\right)_{s,\omega,t_n} = \sum_{i=t_n}^{T}\left(\frac{ISW_{s,\omega}(i)}{(1+WACC)^i}\right)$$
$$ISW_{s,\omega}(i) = \sum_{h=1}^{8760}\left(C_{i,h,\omega,base} - C_{s,i,h,\omega,inv}\right) \quad (16)$$

where $C_{i,h,\omega,base}$ and $C_{s,i,h,\omega,inv}$ are the system operation costs of the base case and investment case, respectively, $ISW_{s,\omega}(i)$ is the annual incremental social benefit, $PV(ISW)_{s,\omega,t_n}$ is the present value of the ISW by executing the investment portfolio in the year t_n and T is the investment horizon. In each case, the subscripts correspond to the hth hour, ith year, ωth realization for the sth investment strategy, respectively.

Afterwards, taking $PV(ISW)_{s,\omega,t_n}$ as the underlying asset (state variable X_τ), the ROV is applied in order to quantify the value of the strategic flexibility embedded in the investment alternatives, i.e., the postponement option in traditional transmission expansions and the FACTS-related options in those cases where the investment portfolio includes these controllers.

In order to illustrate the proposed appraisal procedure, two expansion alternatives are considered: a FACTS device and/or a TL. These investment opportunities remain open for M years. Therefore, the available mutually exclusive investment strategies to expand the system are: to invest in the FACTS devices first (S_1); to invest in the TL first or (S_2); and to invest in the FACTS and TL jointly (S_3).

It is important to note that all the evaluated strategies include the option to invest in both: TL and TCSC. Then the final transfer capacity added to the system, and consequently the performance, could be considered the same in all of them. In other words, it is possible to initially invest in any of the first two options and in successive years, prior to the expiration of the option, to invest in the other. This means that the execution of any of the two alternatives (FACTS or TL) separately creates the option of investing in the other alternative subsequently. This is the flexibility of investing in stages and must be considered in the assessment. Additionally, the FACTS alternative has the option of relocation and abandon.

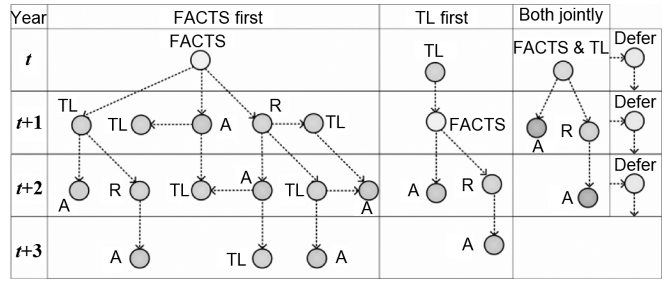

Fig. 2. Strategies—option map. (R: Relocate option, A: Abandon option).

The mapping option of a FACTS investment is illustrated in Fig. 2. The diagram shows the options which become available once the FACTS device is installed. It should be noted that the deferral option is present at each decision-making stage, and its execution means to postpone all the remaining available options in that period to the next one.

Fig. 2 also depicts the mapping option of the remaining investment strategies: investing in the TL first and investing in the TL and FACTS jointly, respectively. In all cases, the option maturity is three years.

Conversely to the TL investments, the flexibility added by the FACTS appears just once the investment is executed and its strategic flexibility is available after the investment expenditure has been committed. The alternatives with FACTS allow for making investments in stages, retaining flexibility for managing uncertainties during the whole planning horizon. For this reason, FACTS-related options reinforce the signal of immediate investment execution.

On the contrary, the value of the postponement option in expansion alternatives where these options are not available is considerable due to the huge uncertainties on the investment performance and the fact that the flexibility is lost in the moment of the investment execution. This suggests that planners should "wait-and-see" until a substantial portion of the long-term uncertainty is resolved. Bellman equations for the evaluation of the options are given below

Option to invest first in the FACTS ($\mathbf{S}_1$):

$$F_F(t_n, X_{t_n}) = \max\left\{\begin{array}{l}\Pi_F\left(t_n, X_{t_n}\right) + \cdots \\ \max\left(\begin{array}{l}F_R\left(t_{n+1}, X_{t_{n+1}}\right) \\ \cdots ; F_A\left(t_{n+1}, X_{t_{n+1}}\right) \\ \cdots ; F_{TL}^{F}\left(t_{n+1}, X_{t_{n+1}}\right)\end{array}\right) \cdot df \\ \cdots ; \mathbb{E}_{t_n}^{*}\left[F_F\left(t_{n+1}, X_{t_{n+1}}\right)\right] \cdot df\end{array}\right\}. \quad (17)$$

Option to invest first in the TL ($\mathbf{S}_2$):

$$F_{TL}(t_n, X_{t_n}) = \max\left\{\begin{array}{l}\Pi_{TL}\left(t_n, X_{t_n}\right) + \cdots \\ F_F^{TL}(t_{n+1}, X_{t_{n+1}}) \cdot df; \cdots \\ \mathbb{E}_{t_n}^{*}\left[F_{TL}\left(t_{n+1}, X_{t_{n+1}}\right)\right] \cdot df\end{array}\right\}. \quad (18)$$

Option to invest in the FACTS & TL Jointly ($\mathbf{S}_3$):

$$F_{TL\&F}(t_n, X_{t_n}) = \max\left\{\begin{array}{l}\Pi_{TL\&F}\left(t_n, X_{t_n}\right) + \cdots \\ \max\left(\begin{array}{l}F_R^{TL\&F}(t_{n+1}, X_{t_{n+1}}); \\ \cdots F_A^{TL\&F}(t_{n+1}, X_{t_{n+1}})\end{array}\right) \cdot df \\ \cdots ; \mathbb{E}_{t_n}^{*}\left[F_{TL\&F}\left(t_{n+1}, X_{t_{n+1}}\right)\right] \cdot df\end{array}\right\} \quad (19)$$

where $F_m^n(t_n, X_{t_n})$ is the option value and $\Pi_m^n(t_n, X_{t_n})$ the profit value, for the option m (F: FACTS, TL: transmission line, R: FACTS relocation, A: FACTS abandon) at the state n (F: FACTS investment done, TL: line investment done, Ab: FACTS abandon done). Expanding (17) yields

$$F_R(t_n, X_{t_n}) = \max \left\{ \begin{array}{l} \Pi_R\left(t_n, X_{t_n}\right) + \cdots \\ \max \left(\begin{array}{l} F_{TL}^R(t_n, X_{t_n}); \cdots \\ F_A(t_{n+1}, X_{t_{n+1}}) \cdot df \end{array} \right); \cdots \\ \mathbb{E}_{t_n}^* \left[F_R\left(t_{n+1}, X_{t_{n+1}}\right)\right] \cdot df \end{array} \right\} \tag{20}$$

$$F_A(t_n, X_{t_n}) = \max \left\{ \begin{array}{l} \Pi_A\left(t_n, X_{t_n}\right) + F_{TL}^A(t_n, X_{t_n}); \cdots \\ \mathbb{E}_{t_n}^* \left[F_A\left(t_{n+1}, X_{t_{n+1}}\right)\right] \cdot df \end{array} \right\} \tag{21}$$

$$F_{TL}^F\left(t_n, X_{t_n}\right) = \max \left\{ \begin{array}{l} \Pi_{TL}^F\left(t_n, X_{t_n}\right) + \cdots \\ \max \left(\begin{array}{l} F_R^{TL\&F}(t_{n+1}, X_{t_{n+1}}); \\ \cdots F_{Ab}^{TL\&F}(t_{n+1}, X_{t_{n+1}}) \end{array} \right) \cdot df \\ \cdots ; \mathbb{E}_{t_n}^* \left[F_{TL}^F\left(t_{n+1}, X_{t_{n+1}}\right)\right] \cdot df \end{array} \right\}. \tag{22}$$

Similarly, expanding (18) and (19):

$$F_F^{TL}(t_n, X_{t_n}) = \max \left\{ \begin{array}{l} \Pi_F^{TL}\left(t_n, X_{t_n}\right) + \cdots \\ \max \left(\begin{array}{l} F_R^{TL\&F}\left(t_{n+1}, X_{t_{n+1}}\right); \cdots \\ F_{Ab}^{TL\&F}\left(t_{n+1}, X_{t_{n+1}}\right) \end{array} \right) \cdot df; \\ \cdots \mathbb{E}_{t_n}^* \left[F_F^{TL}\left(t_n, X_{t_{n+1}}\right)\right] \cdot df \end{array} \right\} \tag{23}$$

$$F_R^{TL\&F}(t_n, X_{t_n}) = \max \left\{ \begin{array}{l} \Pi_R^{TL\&F}\left(t_n, X_{t_n}\right) + \cdots \\ F_{Ab}^{TL\&F,R}\left(t_{n+1}, X_{t_{n+1}}\right) \cdot df; \cdots \\ \mathbb{E}_{t_n}^* \left[F_R^{TL\&F}\left(t_{n+1}, X_{t_{n+1}}\right)\right] \cdot df \end{array} \right\} \tag{24}$$

$$F_A^{TL\&F}(t_n, X_{t_{n+1}}) = \max \left\{ \begin{array}{l} \Pi_A^{TL\&F}\left(t_n, X_{t_n}\right); \cdots \\ \mathbb{E}_{t_n}^* \left[F_A^{TL\&F}\left(t_{n+1}, X_{t_{n+1}}\right)\right] \cdot df \end{array} \right\}. \tag{25}$$

The profit function in the investment cases is given by

$$\Pi_m^n\left(t_n, X_{t_n}(\omega)\right) = PV\left(ISW\right)_{s,\omega,t_n} - I_{s,t_n,\omega} \tag{26}$$

where $I_{s,t_n,\omega}$ is the investment cost of the sth investment strategy at the t_nth year. On the other hand, in the relocation and abandon cases, the profits are computed by

$$\Pi_R^n\left(t_n, X_{t_n}(\omega)\right) = PV\left(ISW_{R,t_n,\omega}\right) - C_{R,t_n,\omega} \tag{27}$$

$$\Pi_A^n\left(t_n, X_{t_n}(\omega)\right) = SV_{t_n,\omega} - PV\left(ISW\right)_{s,\omega,t_n} \tag{28}$$

where C_R, t_n, ω is the relocation cost and $SV_{t_n,\omega}$ is the scrap value of the FACTS devices at the t_nth year. Finally, the LSM approach is applied for solving the RO dynamic programming problem.

V. Valuing a Flexible TIP. Study Case: The Italy-France-Switzerland Interconnected System

The transmission planning is classified as dynamic, if multiple years are considered and the optimal expansion strategy is outlined along several planning stages. The associated dynamic planning problem may be exceedingly complex and large because it must account not only for sizing and placement but also for timing considerations. This results in a large number of variables and restrictions to consider, and requires a huge computational effort to get the solution, especially in real power systems. Few works about dynamic models for real-world transmission planning problems can be found in the technical literature. Normally, reduced network models, carefully calibrated for reproducing actual conditions, are required in order to analyze real investment in complex power systems [1].

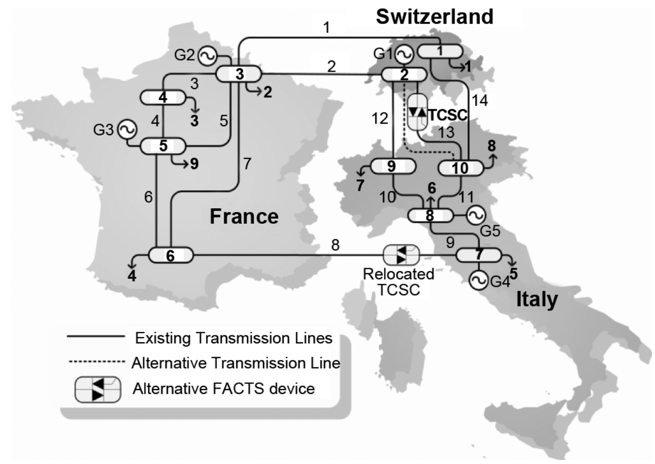

Fig. 3. Ten-bus network with three regions.

A well-known congestion path in Central Europe appears in the interconnection between the Italian electric system and its neighboring countries, France and Switzerland. Italy has to import large quantities of electric energy through these interconnections, due to limited domestic generation capacity. In year 2008, Italy was importing cheap energy through international interconnectors on average 2013.5 GWh monthly from Switzerland and more than 1000 GWh from France [6], [24].

Thus, this section presents a reduced real case study about installing a TCSC in the lines directly connecting France and Switzerland applying the valuation approach presented in the previous sections. The network chosen to replicate the physical conditions around the aforementioned congested link is illustrated in Fig. 3. This system is a ten-bus network with five equivalent generators, eight aggregate loads, and 13 TLs. The parameters of the TLs, the generation units, and the loads were carefully selected in [6] in order to accurately replicate the impact of the congested scenario on the system. The detailed electrical and economic parameters of the network components are the same presented in [6] as well.

Under the analyzed scenario, the TL-13 is congested, being needed to implement a congestion management technique. A long-term solution should be the upgrading of the congested TL. However, this solution involved a large-scale irreversible investment which could be excessive (observe that there is still available transfer capacity on TL-8) during several years, mainly, if the uncertain variable evolution is not the expected. Hence, the deferral of this project, waiting for the unfolding of the uncertainties, could be worthwhile.

TABLE I
GENERATOR COST PARAMETERS [6],[25]

Generator	$a_0(0)$	$a_1(0)$	$a_2(0)$	$p_F(0)$	$\overline{p_F}$	$\sigma^{\ln p^F}$	$\mathbf{P_{max}}$
G1	0	6.9	0.00067	0.2	0.21	0.0319	1200
G2	0	24.3	0.00040	3	2.98	0.107	8000
G3	0	29.1	0.00006	5.51	6.64	0.14	3000
G4	0	6.9	0.00026	0.2	0.21	0.0319	800
G5	0	50.0	0.00150	12.46	17.94	0.129	2000

TABLE II
DURATION AND GROWTH PARAMETERS OF DEMAND [24]

Country	$R^j_{peak}(0)$	σ_{peak}	$R^j_{base}(0)$	σ_{base}
France	1.83	4.99	1.68	1.86
Italy	1.07	6.84	2.011	1.33
Switzerland	1.02	5.79	1.36	1.49

As mentioned before, one possible way of addressing this problem may be the deployment of FACTS. Although new line investments cannot be completely eliminated from long-term transmission expansion plans, by investing in FACTS, the addition of news lines may probably be postponed until more certain information becomes available. Thus, a proper mix of transmission controllers and TL would be required.

Two investment alternatives are evaluated: 1) a new TL between the nodes 2 and 10 (identical to the TL-13); 2) a TCSC of 365 MVar connected to the TL between nodes 2 and 10 with the option to relocation between nodes 6 and 7.

Then, the three mutually exclusive options (strategies S_1, S_2, S_3), which was exposed in Section V, must be evaluated.

Generators 1 and 4 are aggregate hydro units, generator 2 aggregated nuclear plants, generator 3 represent aggregate lignite-based thermal units, and generator 5 are gas-fired thermal units. Table I provides the generator parameters needed to conduct the temporal generation cost simulation.

Two demand periods are considered, base and peak. The period duration remains constant (8 h peak and 16 h base load) over the investment horizon. Probabilistic parameters for simulating the annual growth rate are provided in Table II and correlation matrix as follows:

$$\Theta_{peak} = \begin{bmatrix} 1 & 0.44 & 0.28 \\ 0.44 & 1 & 0.77 \\ 0.28 & 0.77 & 1 \end{bmatrix}$$

$$\Theta_{base} = \begin{bmatrix} 1 & 0.0016 & 0.409 \\ 0.0016 & 1 & 0.026 \\ 0.409 & 0.026 & 1 \end{bmatrix}.$$

TL costs have been modeled as a linear function of the TL length [5]. The capital expenditure is considered to be 600 k€/km for a new 380 kV TL. The line length is about 250 km; therefore, the TL cost is 150 M€.

Within this paper, the initial outlay including installation costs function for the TCSC is considered the same as what is proposed in [6]. Similarly, the scrap value of the FACTS device and its relocation cost are considered equal to the 40% of and 20% the total FACTS capital cost, respectively.

Under energy deficit scenarios, the zonal price is set at the value of lost load (VOLL), which has been assumed to be 500 €/MWh. It is considered as maturity for all investments options three years and 15 years as the investment horizon, with a discount rate equal to 12%/yr.

The Monte Carlo stopping criterion is defined with a maximum relative error of 1.5% with a confidence interval of 95% [20]. Hence, 20 000 simulations were necessary for satisfying the convergence criterion.

TABLE III
RANKING OF STRATEGIES BY APPLYING THE PROPOSED EVALUATION APPROACH AND DE TRADITIONAL APPRAISAL (M€)

Strategy	Expected Option Value	Expected NPV value	Flexibility value
S_1	672.69	590.49	82.20
S_2	615.92	602.43	13.49
S_3	612.13	562.44	49.69

A. Result Analysis

Traditional investment appraisal methods, such as NPV, suggest S_2 as the optimal investment choice. Notwithstanding, taken into account the strategic flexibility provided by FACTS, the RO valuation determines the S_1 as the optimal decision, as shown in Table III. This table also provides the flexibility value for the three investment strategies. The economic value of the flexibility provided for each investment strategy is given by subtracting the expected NPV of the expected option value.

It can be noticed that the investment alternative S_1, investing in FACTS first, has the higher flexibility value. This fact is mainly due to the flexibility of FACTS remains after the investment has been executed allowing a better adaption to possible adverse scenarios in the long-term.

Thus, FACTS devices allow making expansions, retaining flexibility for managing uncertainties of the TI problem.

On the contrary, in TL expansion alternatives, these options are not available and only the deferral option is present. Accordingly, the economic value of such expansion projects is lower than more flexible investment portfolios.

Table IV depicts the possible composition of the RO portfolios and its respective value. Thus, for instance, the composition TL-F-R-A means that the option to invest in the TL, FACTS, relocation, and abandon are available. It is important to bear in mind that in all cases, the deferral option is considered available.

As can be also noted in Table IV, the S_1 value decreases when are unavailable the abandon and relocation options. This means that these options are valuable and its valuation is relevant. Nevertheless, in this particular case, S_1 value is always higher than the values of S_2 and S_3.

In a portfolio which includes FACTS, the most important option is probably the option to defer the new TL. This can be observed by comparing the option values with and without TL in their set of options. In fact, if both investment, FACTS and TL, were mutually exclusive, then the optimal decision would

TABLE IV
OPTION VALUE AND THE COMPOSITION OF THE OPTION PORTFOLIO

Strategy	**Available Options Value** [M€]								
	TL-F-R-A	**TL-F-R**	**TL-F-A**	**TL-F**	**F-R-A**	**F-R**	**F-A**	**F**	**TL**
S_1	672.69	661.14	652.07	648.92	591.43	591.20	591.42	591.12	
S_2	615.92	615.92	610.70	610.70					610.38
S_3	612.13	584.31	609.04	575.92					

TABLE V
LOAD PARAMETERS [6]

Bus	**P [MW]**
1	110
2	1300
3	1300
4	200
5	2600
6	3600
7	1100
8	1900

TABLE VI
TRANSMISSION LINE PARAMETERS [6]

Line	**R** [p.u.]	**X** [p.u.]	$\mathbf{P_{max}}$ [MW]
1	0.04	0.10	3000
2	0.08	0.12	3500
3	0.01	0.10	1780
4	0.02	0.17	2150
5	0.02	0.17	2150
6	0.02	0.17	2800
7	0.02	0.17	3500
8	0.02	0.16	3500
9	0.02	0.25	2000
10	0.02	0.25	2260
11	0.01	0.07	3500
12	0.01	0.07	2260
13	0.01	0.14	1580
14	0.04	0.27	2000

be S_2. This decision is made by comparing the option values S_1 (F-R-A) with S_2 (TL).

From the same option portfolio composition, S_2 (TL), it is possible to obtain the value of the deferral option of the TL. By comparing this value with the S_2 flexibility value, it is easy to note that the largest flexibility of the strategy to invest in TL first is the TL deferral option. The high value of keeping open the wait-and-see option is consistent with the observed low investment activity in most transmission systems.

VI. CONCLUSION

This paper presents a new framework for assessing flexible investments in the transmission network under uncertainties accounting for the economic value of the option of relocation and abandon of FACTS devices.

It was shown that the traditional NPV method may be wrong when assessing TIs, since the presence of uncertainties dramatically increases the risk involved in large-scale irreversible decisions. Flexibility for reconsidering, relocating, or abandoning a TI project in light of unfolding information is highly valuable in such an uncertain environment.

The option values have their own source from the fact that they establish a floor against possible project losses. A real option valuation framework has been developed, using for the first time in power investments the novel LSM approach for solving the related large-scale dynamic programming optimization problem.

It has been verified in a real study case that improved adaptability levels to the uncertain scenarios may be obtained by strategically mixing FACTS devices and TLs investments along the planning horizon.

These expansion alternatives induce the investment execution in stages instead of only deferring large TL projects. Thereby, a proper tradeoff between large TL investments and flexibility offered by FACTS can be achieved. This allows a progressive adaptation of the transmission grid to the uncertain long-term development of power markets.

APPENDIX

Table V lists the load parameters from [6], and Table VI lists the transmission line parameters from [6].

REFERENCES

[1] G. Latorre, R. Cruz, J. Areiza, and A. Villegas, “Classification of publications and models on transmission expansion planning,” *IEEE Trans. Power Syst.*, vol. 18, no. 2, pp. 938–946, May 2003.

[2] G. Shrestha and P. Fonseka, “Flexible transmission and network reinforcements planning considering congestion alleviation,” *Proc. Inst. Elect. Eng., Gen., Transm., Distrib.*, vol. 153, no. 5, pp. 591–598, Sep. 2006.

[3] L. Gyugyi, “Dynamic compensation of AC transmission lines by solid-state synchronous voltage sources,” *IEEE Trans. Power Del.*, vol. 9, no. 2, pp. 904–911, Apr. 1994.

[4] B. T. Ooi, G. Joos, F. D. Galiana, D. McGillis, and R. Marceau, “FACTS controllers and the deregulated electric utility environment. In electrical and computer engineering,” in *Proc. IEEE Canadian Conf.*, May 1998, vol. 2, pp. 597–600.

[5] A. L’Abbate, G. Fulli, and E. Handschin, “Economics of FACTS integration into the liberalised European power system,” in *Proc. 2007 IEEE Lausanne Power Tech*, Lausanne, Switzerland, Jul. 2007, pp. 885–890.

[6] C. Schaffner, “Valuation of controllable devices in liberalized electricity markets,” Ph.D. dissertation, ETH Switzerland, Zurich, Switzerland, 2004, Diss. ETH No. 15850.

[7] S. Olafsson, “Making decisions under uncertainty—Implications for high technology investments,” *BT Technol. J.*, vol. 21, pp. 170–183, 2003.

[8] F. Longstaff and E. Schwartz, “Valuing American options by simulation: A simple least-squares approach,” *Rev. Fin. Stud.*, vol. 14, pp. 113–47, 2001.

[9] A. Gamba, *Real Options Valuation: A Monte Carlo Approach, Working Paper*. Verona, Italy: Univ. Verona, 2003, pp. 1–49.

[10] A. Rodrigues and M. Rocha, *The Valuation of Real Options With the Least Squares Monte Carlo Simulation Method*. Braga, Portugal: Management Research Unit, Univ. Minho, 2006.

[11] G. Cortazar, M. Gravet, and J. Urzua, "The valuation of multidimensional American real option using the LSM simulation method," *Comput. Oper. Res.*, vol. 35, pp. 113–129, Jan. 2008.

[12] A. Botterud, M. Ilic, and I. Wangensteen, "Optimal investments in power generation under centralized and decentralized decision making," *IEEE Trans. Power Syst.*, vol. 20, no. 1, pp. 254–263, Feb. 2005.

[13] M. Yang, W. Blyth, R. Bradley, D. Bunn, C. Clarke, and T. Wilson, "Evaluating the power investment options with uncertainty in climate policy," *Energy Econ.*, vol. 30, no. 4, pp. 1933–1950, Jul. 2008.

[14] G. Blanco, F. Olsina, O. Ojeda, and F. Garcés, "Transmission expansion planning under uncertainty—The role of FACTS in providing strategic flexibility," in *Proc. 2009 IEEE Bucharest PowerTech*, Bucharest, Romania, 2009, pp. 1–8.

[15] S. Stoft, "Transmission investment in a deregulated power market," in *Competitive Electricity Markets and Sustainability*. Cheltenham, U.K.: Edward Elgar, 2005, ch. 4, pp. 87–130.

[16] S. Blumsack, "Network topologies and transmission investment under electric-industry restructuring," Ph.D. dissertation, Carnegie Mellon Univ., Pittsburgh, PA, 2006.

[17] T. A. Luehrman, "Strategy as a portfolio of real options," *Harvard Bus. Rev.*, pp. 76–99, 1998.

[18] L. M. Tolbert, T. J. King, B. Ozpineci, J. B. Campbell, G. Muralidharan, D. T. Rizy, A. S. Sabau, H. Zhang, W. Zhang, Y. Xu, H. F. Huq, and H. Liu, *Power Electronics for Distributed Energy Systems and Transmission and Distribution Applications*. Oak Ridge, TN: Eng. Sci. Technol. Div., Oak Ridge Nat. Lab., 2005, pp. 35–36.

[19] A. Dixit and R. Pindyck, *Investment Under Uncertainty*. Princeton, NJ: Princeton Univ. Press, 1994, pp. 93–125.

[20] G. Fishmerman, *Monte Carlo: Concept, Algorithms and Applications*. New York: Springer, 1996, pp. 21–234.

[21] C. Weber, *Uncertainty in the Electric Power Industry*. New York: Springer, 2005.

[22] R. D. Zimmermann, C. Murillo-Sánchez, and D. Gan, Matpower a Matlab Power System Simulation Package, User's Manual 3.2, av, 2007. [Online]. Available: http://www.pserc.cornell.edu/matpower/manual.pdf.

[23] X. Wang, Y. Song, Q. Lu, and Y. Sun, "Optimal allocation of transmission rights in systems with FACTS devices," *Proc. Inst. Elect. Eng., Gen., Transm., Distrib.*, vol. 149, no. 3, pp. 359–366, May 2002.

[24] ENTSOE. [Online]. Available: http://www.entsoe.eu.

[25] IER, Energy System Development in Germany, Europe and Worldwide, 2007.

Gerardo Blanco (GS'08) received the Electromechanical Engineer degree from the National University of Asunción, San Lorenzo, Paraguay, in 2004 and the Ph.D. degree from the Institute of Electrical Energy (IEE), National University of San Juan (UNSJ), San Juan, Argentina, in 2010.

He was a Visiting Researcher at the Institute of Power System & Power Economics, TU Dortmund, Dortmund, Germany. Presently, he is full-time professor of the Polytechnic Faculty, National University of Asunción. His research interests are power investment under uncertainty, energy policies, and risk management.

Fernando Olsina received the Mechanical Engineering degree in 2000 from the National University of San Juan (UNSJ), San Juan, Argentina, and the Ph.D. degree in electric power engineering in 2005 from the Institute of Electrical Energy (IEE), UNSJ.

He was a Visiting Researcher at IAEW, the RWTH Aachen, Aachen, Germany, and at Lehrstuhl für Energiewirtschaft (EWL) at Universität Duisburg-Essen, Essen, Germany. His research interests focuses on power market modeling, reliability evaluation of power systems, stochastic price simulation, and investments under uncertainty.

Dr. Olsina is presently a member of the Argentinean Research Council (CONICET).

Francisco Garcés received the Electromechanical Engineering degree from the University of Cuyo, Mendoza, Argentina, in 1974 and the Dr.-Ing. degree from the Aachen University of Technology (RWTH), Aachen, Germany, in 1982.

Presently, he is a Vice-Director of the Institute of Electrical Energy, National University of San Juan, San Juan, Argentina, and Head of the Reliability & Risk Management Group. His main research interests are power system reliability and reserve calculations.

Christian Rehtanz (M'96–SM'05) received the diploma degree in electrical engineering in 1994 and the Ph.D. degree in 1997 at the TU Dortmund University, Dortmund, Germany.

From 2000, he was with ABB Corporate Research, Switzerland, and from 2003 Head of Technology for the global ABB business area Power Systems. From 2005, he was Director of ABB Corporate Research in China. Since 2007, he has been a Professor and Head of the Institute for Power Systems and Power Economics at the TU Dortmund University. His research activities include technologies for network enhancement and congestion relief like stability assessment, wide-area monitoring, protection, and coordinated FACTS- and HVDC-control.