Paper accepted for presentation at 2009 IEEE Bucharest Power Tech Conference, June 28th - July 2nd, Bucharest, Romania

Transmission expansion planning under uncertainty – The role of FACTS in providing strategic flexibility

Gerardo A. Blanco, *Graduate Student Member, IEEE,* Fernando G. Olsina, Osvaldo A. Ojeda and Francisco F. Garcés

***Abstract*—Efficient and well-timed investments in electric transmission networks - that suitably cope with the large power market uncertainties- is currently an open issue of considerable research interest. Strategic flexibility for seizing opportunities and cutting losses contingent upon the market evolution is of enormous value when assessing investments under uncertainties. In this sense, FACTS devices appear as an effective means of adding strategic flexibility to the transmission expansion planning. This article proposes an expansion planning approach which assesses the option value of deferring expansion investments in transmission lines while gaining flexibility by investing in FACTS devices. In a numerical example, a conventional expansion alternative (only transmission lines) is compared to a flexible investment alternative (transmission lines & FACTS) in order to shed light on the investment signals that each approach provides. The article shows that a suitable combination between lines and FACTS could generate flexible investments in smaller stages, instead of infrequent investments in large transmission expansion projects, which facilitates the progressive adaptation of the electric network to the changing scenarios.**

***Index Terms*— FACTS, LSM Monte Carlo Valuation, Monte Carlo Simulation, Real Options, Strategic Flexibility, Transmission Investment, Uncertainty.**

I. Introduction

Since the liberalization of the power markets, the transmission system plays a key role in determining the degree of market competition as well as the overall system economies and reliability levels. Network upgrades are commonly motivated by arbitrage reasons, congestion and operational cost reductions as well as the preservation of adequate reliability levels [1].

For these reasons, the adequate expansion of transmission networks have become an issue of concern in the electricity supply industry.

Under the classical view, the Transmission Expansion Planning (TEP) problem can be formulated as a large-scale stochastic, nonlinear, mixed-integer optimization problem. A large number of algorithms and approaches have been devised for solving this complex problem [2]. However, the theory and tools for transmission planning are still below the practical requirements of the new power markets. This is particularly true in aspects such as the flexibility and dynamic nature of the transmission planning process and the introduction of flexible transmission devices [2].

Traditional upgrades of the grid infrastructure are primarily proposed in the form of investments in new transmission lines. Nevertheless, expanding the transmission network in this conventional manner may not always be the best way to deal with network constraints especially those that arise due to the lack of control over grid flows. Hence, in highly meshed systems, a new transmission line can lead to congestions in geographically distant, and apparently unrelated, network locations.

One possible way of dealing with these problems is the deployment of Flexible AC Transmission Systems (FACTS), which provide an alternative to building new transmission lines. FACTS are power electronics–based devices for the control of voltages and/or currents, enhancing controllability and increasing power transfer capability [3].

Nowadays, the development experienced in power electronic components, particularly regarding the progressive reduction of costs, has made possible to integrate FACTS devices to electric power systems.

Investments in FACTS technologies exhibit some desirable features that considerably increase their flexibility: modularity, scalability, short construction times, high levels of reversibility and small financial commitments).

Hence, the use of FACTS adds a new set of options to the network expansion planning that significantly enhance its strategic flexibility. Options such as postponement, abandonment, operational flexibility, or relocation offer an additional value to FACTS investments, which should be fairly valued [3].

The inevitable uncertainties associated with the transmission expansion planning are better managed with investments that provide flexibility. As new information arrives, planners need the flexibility to change operating strategies to exploit favorable opportunities or to cut losses in the case of adverse scenarios. This flexibility may include various actions at different stages of the planning horizon, such as the options to defer, expand, reduce or even abandon the project. This flexibility to adapt to changing market conditions has a substantial value, which has to be considered when a plan implementation is being decided. It is thus essential that flexibility be properly quantified. Any attempt to quantify investment flexibility almost naturally leads to the concept of Real Options [4].

The Real Option Valuation (ROV) technique provides a well-founded framework –based on the theory of financial

This work was supported in part by the German Academic Exchange Service (DAAD) and the Argentinean Research Council (CONICET).

G. Blanco, F. Olsina, A. Ojeda and F. Garcés are with the Instituto de Energía Eléctrica (IEE) at Universidad Nacional de San Juan (UNSJ), Argentina (E-mail: gblanco@iee.unsj.edu.ar).

options- to assess strategic investments under uncertainty. It quantitatively takes into account investment risks and the value of the open options for planners.

However, real option models usually present a higher complexity than their financial counterpart. In fact, real investments often exhibit a more intricate set of interacting options, which make them more complicated to assess.

In this sense, Longstaff *et al.* [5] have proposed a novel method for solving American options, based on stochastic simulation, which have been successfully applied to solving financial options. In the recent years, Gamba [6] presented a new approach for valuing a wide set of investment problems with many embedded real options taking into account the interaction and strategic interdependence between the options.

This paper explores the applicability of these approaches to the transmission expansion problem with many embedded real options and FACTS devices as investment alternative. This article aims at shedding light on the role of FACTS devices within the transmission expansion problem in order to improve the flexibility of the transmission expansion plans.

II. Characterization of Transmission Investments

The transmission investment problem should be characterized according to the nature of the investment involved. Economies of scale, long capital recovery time, long-run uncertainties, low adaptability, lumpiness, irreversibility and postponement options are inherent features of transmission investments [7].

As a consequence of the significant economies of scale, transmission investment should respond to load growth by investing in large transmission projects infrequently with low adaptability. Therefore, the chance of incurring in either over- or under-investment is significantly increased. Transmission facilities are highly vulnerable to the ongoing uncertainties affecting the key driving market variables, e.g. future demand, fuel costs and generation investments, for instance.

Moreover, transmission investments, once executed, are considered irreversible. In fact, it is very unlikely that transmission equipment can be utilized for other purposes or relocated if conditions turn out to be unfavorable. Under these circumstances, transmission equipments could not be sold off without assuming significant losses on its nominal value [8].

Consequently, the valuation of transmission expansion should be treated as a risk management problem, in which flexible investments act as a hedge against adverse scenarios. In case of unfavorable circumstances, this flexible investment should let the planner, either make adjustments or changes in an easy and economical way or withstand such scenarios with no changes [9].

The option of deferring the investment decision is the most prominent flexible feature of traditional transmission expansions. Typically, transmission investments are not now-or-never opportunities. Hence, keeping the investment option open has considerable value. Accordingly, transmission investments should be treated in an analogous way that a American call option [8]. In fact, the opportunity cost incurred when the ability of deferring is lost, must be evaluated together with other costs and benefits.

In most cases, the substantial value of the postponement option leads to retain flexibility by delaying the transmission investment decision. This can entail a waiting period of several years until new transmission network capacity is effectively added to the system.

Consequently, it is necessary to seek new flexible investment alternatives, which combined with the conventional expansion, allow planners to efficiently manage the uncertainties along the planning horizon.

III. Investment in FACTS Devices

The possibilities that open the FACTS devices in the liberalized environment are currently under intensive research. A review of the publications in the field shows that FACTS have a major influence on many aspects of electricity market behavior. In numerous papers, the impact of the FACTS on congestion management is analyzed, as well as their ability to improve controllability and the reliability of interconnected systems [3].

Particularly, the use of FACTS could add a set of options to the network investments that improve its flexibility. Those options offer substantial additional value to these investments and they are analyzed in this article.

Despite the many advantages offered by FACTS devices, there are too few proposals for integrating them in the network expansion planning. Some contributions have recently been made in this area. These show that the expansion alternative with FACTS devices presents a good performance compared with traditional network reinforcement [10]. However, all these papers utilize the Net Present Value method (NPV) and consider neither the uncertainty on future market conditions nor the flexibility value added by the FACTS devices.

Therefore, valuing the gained flexibility in transmission expansion plans by investing in FACTS and deferring conventional transmission projects is a key issue that still remains uninvestigated.

IV. Valuing Flexible Investment under uncertainty

It has been demonstrated that the classic NPV valuation method can be misleading for assessing irreversible investments exhibiting managerial flexibility [13].

The ROV is a modern investment appraisal technique for economic valuation of projects under uncertainty, which applies methods derived from finance theory to the valuation of capital investments. The real options arise from degrees of freedom which a decision maker has at hands, contingent upon future events [11].

In the early stages of the ROV, valuation was normally confined to the options for which solutions of the financial could directly be applied. This was done mainly using few underlying assets and simple options with European features or American perpetual options [12]. However, an investor is normally confronted with a vast opportunity set. Hence investment projects are a portfolio of options; frequently depending on several stochastic variables.

The introduction of multiple interacting options into the real options models increases the difficulty of solving them, making traditional numerical approaches inadequate. Nevertheless, simulation procedures for successfully solving multiple American options have been proposed. One of the most promising approaches is the Least Square Monte Carlo (LSM) method proposed by Longstaff and Schwartz [5].

LSM method is based on Monte Carlo simulation and uses least squares linear regression to determine the optimal stopping time in the making decision process. Moreover, this approach has the feature of being a very intuitive and flexible tool.

Recently, Gamba [6] proposed a model which extending the LSM approach decomposes complex multiple real options (with interacting options) into simple hierarchical sets of individual options. The decomposition principle can be used by applying any kind of methodology based on dynamic programming and Bellman equation [12].

Hence, the main contribution of our work is a new way to map a complex real option problem in power transmission investments into a set of simple options and a way to comply with the hierarchical structure of the options.

A. The Least Square Monte Carlo approach framework

The value of an American option, with payoff $\Pi(\tau, X_\tau)$, that can be exercised from t until T is:

$$F(t,X_\tau)=\max_{\tau}\left\{\mathrm{E}_t^*\left[\Pi\left(\tau,X_\tau\right).(1+r)^{-(\tau-t)}\right]\right\} \qquad (1)$$

where τ is the optimal stopping time ($\tau \in [t, T]$) and $\mathrm{E}_t^*[.]$ denote the risk neutral expectation conditional on the information available at t. The discount factor between two periods is $df=(1+r)^{-1}$, where r is the discount rate.

As is exposed in [12], the LSM approach proposed a Monte Carlo simulation algorithm to value the option described by the equation (2). That equation can be expressed in a discrete way dividing the time of the maturity (T) in N discrete intervals. Then the underlying asset evolution is simulated following Ω realizations. Contemplating that option can only be exercised in discrete times, into the interval [0, T].

Thus, the optimal stopping policy is obtained using 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*" [13]. This can be expressed as:

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

Expressing the continuing value by:

$$\Phi\left(t_n,X_{t_n}\right)=\mathrm{E}_{t_n}^*\left[F\left(t_{n+1},X_{t_{n+1}}\right)\right].df \qquad (3)$$

with:

$$\Phi\left(T,X_T\right)=0 \qquad (4)$$

The optimal stopping time on each realization ($\tau(\omega)$), is found, beginning at T and proceeding backwards, applying the following rule:

$$\text{if}\quad \Phi\left(t_n,X_{t_n}(\omega)\right)\le\Pi\left(t_n,X_{t_n}\right)\quad\text{then}\quad \tau(\omega)=t_n \qquad (5)$$

At the maturity time, the options are no longer available, consequently, the continuation value equals zero. Prior to T at t_n, the option holder must compare the payoff from the immediate exercise ($\Pi(t_n,X_{t_n})$), with the continuation value ($\Phi(t_n,X_{t_n})$). When the decision rule (5) holds the stopping time $\tau(\omega)$ is updated. The value of the American option is then calculated as the average of the values over all realizations:

$$F(0,x)=\frac{1}{\Omega}\sum_{w=1}^{\Omega}\Pi\left(\tau(\omega),X_{\tau(\omega)}\right).(1+r)^{-(\tau(\omega))} \qquad (6)$$

The problem boils down to one of finding the expected continuation value at (t, X_t), in order to apply the condition (5). Here is where the LSM makes its main contribution; this method computed the continuation for all previous time-stages by regressing the discounted future option values on a linear combination of functional forms of current state variables. Considering that the way these functional forms is not evident, the most common implementation of the method is simple powers of the state variable (monomial) [5], [6], [12].

As is shown in [14], let L_j, with j=1,2,…,J be the orthonormal basis of the state variable X_t used as regressors to explain the realized present value in the ω-th realization, then the least square regression is equivalent to solving the following optimization problem :

$$\min_{\varphi}\sum_{w=1}^{\Omega}\left[\Pi\left(t+1,X_{t+1}(\omega)\right).df-\sum_{j=1}^{J}\varphi_j L_j(X_t(\omega))\right]^2 \qquad (7)$$

Then the optimal coefficients φ^* are used to estimate the expected continuation value $\Phi^*\left(t,X_t(\omega)\right)$:

$$\Phi^*\left(t,X_t(\omega)\right)=\sum_{j=1}^{J}\varphi_j^* L_j(X_t(\omega)) \qquad (8)$$

Working backwards until t=0, the optimal decision policy on each path -choosing the maximum between two values: the immediate exercise and the expected continuation value- can be computed.

B. Multi-option problems

As said before, Gamba in [6] has presented an extension of the LSM method to value independent, compound and mutually exclusive options, as well as switching problems. According to that approach, it can be defined [12]:

Independent option: The value of a portfolio of independent options is the sum of individual options, computed by the LSM. Only in this case, value additivity holds, even when the underlying assets are not independent.

Compound Option: Let a portfolio of H compounded options, where the execution of h-th option origins the right to exercise the subsequent (h+1)-th option. The payoff $\Pi_h(t,X_t)$ of the h-th, must taken into account the value of the option ($h+1$)-th. These options are valued applying the LSM approach. Consequently, the value of the option can be calculated according to:

$$F_h(t,X_t)=\max_{\tau\in[t,T_h]}\left\{\mathrm{E}_{t_n}^*\left[\Pi_h\left(\tau,X_\tau\right)+F_{h+1}\left(\tau,X_\tau\right)\right].df\right\} \qquad (9)$$

Hence, the Bellman equation for this sort of portfolio of real options can be expressed by:

$$F_h(t_n,X_{t_n})=\max\left\{\begin{matrix}\Pi_h\left(t_n,X_{t_n}\right)+F_{h+1}(t_n,X_{t_n}),\ldots\\ \mathrm{E}_{t_n}^*\left[F_h\left(t_{n+1},X_{t_{n+1}}\right)\right].df\end{matrix}\right\} \qquad (10)$$

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. Typical examples of that kind of options are the expansion and abandon options. Thus, the problem is extended to find both the optimal stopping and the optimal option. Therefore, the control is a bi-dimensional variable (τ,ζ), where τ is a stopping time in [t, T_h] and $\zeta \in \{1, 2,\ldots, H\}$. The value of the option to choose the best, among H mutually exclusive options, is:

$$G(t, X_t) = \max_{(\tau,\varsigma)} \left\{ \mathrm{E}^*_{t_n} \left[F_\varsigma(\tau, X_\tau) \right] .df \right\} \quad (11)$$

The Bellman equation of a set of mutually exclusive options is given by:

$$G_h(t_n, X_{t_n}) = \max \left\{ \begin{array}{l} F_1(t_n, X_{t_n}), \ldots, F_H(t_n, X_{t_n}), \ldots \\ \mathrm{E}^*_{t_n} \left[G_{h+1}(t_{n+1}, X_{t_{n+1}}) \right] .df \end{array} \right\} \quad (12)$$

Each $F_h(t_h,X_h)$ and the continuation value (Φ_n) is obtained by the LSM approach exposed before.

V. Valuation of Flexible Investment Portfolios in Transmission (IPT) including FACTS devices

An initial premise of this research considers a thermal power system where the transmission network is operated by an Independent System Operator (ISO) which proposes the investment portfolios to be evaluated.

The Flexible Investment Portfolios in Transmission (IPT) value will be defined by the increase (or decrease) of the social welfare resulting from the investment execution. This incremental social welfare will be quantified through the generation cost differences between the base scenario (without investment) and investment scenario.

The proposed methodology essentially consists in a model divided in two main modules. These modules are the following:

A. Technical-economic analysis module:

This research develops the mathematical algorithms for assessment of IPTs considering FACTS devices performance under uncertainty on futures scenarios.

In this module, the uncertain behavior of the power market is simulated through the Monte Carlo method.

The evolution of relevant uncertain variables will be modeled through appropriate stochastic processes, which are summarized below:

Demand growth rate: Electricity demand is one of the key factors in the performance of power markets and their investments.

This paper considers two blocks of demand (peak and base), and the duration of each block is assumed constant during the evaluation. The demand evolution on each area of the electrical system is modeled as a function of the stochastic growth rate. This growth rate is modeled as a multivariate stochastic process that takes into account the correlation among geographic areas of the system [15]. The multivariate stochastic process of the growth rate is illustrated below:

$$dR^j(t) = \mu_{R^j}(t).dt + \Theta.dW; \; R^j(t) = \begin{bmatrix} R^j_{1,p}(t) & R^j_{1,b}(t) \\ \vdots & \vdots \\ R^j_{n,p}(t) & R^j_{n,b}(t) \end{bmatrix} \quad (13)$$

where: $R^j(t)$ is the vector of stochastic growth rates in the instant t and j-th realization, $R^j_{n,p}(t)$ and $R^j_{n,b}(t)$ growth rates in peak demand and base of the n-th instant t in the j-th realization respectively and $\mu_{R^j}(t)$ representing vector drift instant t. The vector of the Wiener process in t of the j-th realization is represented by dW. Θ is defined by an nxn lower triangular matrix, which satisfies $\Upsilon = \Theta . \Theta^{\mathrm{T}}$, where Υ is given by nxn covariance matrix, given by $\Upsilon = \Psi.\Gamma.\Psi^{\mathrm{T}}$. Ψ is the diagonal matrix of variances, with $\Psi(i,i) = \sigma^2(i)$ (the variance of i), and Γ the matrix of correlations between areas, with $\Gamma(i,j) = \rho_{i,j}$ (the correlation between areas i and j).

Generation cost: This work considers a thermal generation system using fossil fuels as primary energy source. The fuel price is modeled by a mean reversion stochastic process [15].

$$dp_F(t) = \alpha\left(\overline{p_F} - p_F(t)\right) + \sigma^{p^F} dW \quad (14)$$

where α is the speed of reversion to the mean, σ^{p^F} is the volatility of fuel prices, and $\overline{p_F}$ is the normal level of the fuel price (p_F), i.e. the level to which p_F tends to revert.

The cost of generating a thermal generation unit typically includes fuel costs and startup costs. Commonly, this cost is linked with the fuel prices through the input-output function of the generating unit (IO [MBtu/h]), according to the following expression [15]:

$$\begin{aligned} C\left(q\ (t), p_F(t)\right) &= \left(a_0 + a_1.q\ (t) + a_2.q(t)^2\right).p_F(t) \\ C\left(q\ (t), p_F(t)\right) &\equiv IO\left(q(t)\right).p_F(t) \end{aligned} \quad (15)$$

Where $C\left(q\ (t), p_F(t)\right)$ is the generation cost at a production level of $q\ (t)$ [MW] and a fuel price of p_F (t).

Electric system components availability: Stochastic modeling of the failure behavior of network components should include the average time of operation and reparation. The operation states with unavailability of components are important in evaluating investments in transmission systems under the new market scenarios. It is possible to prove that peak prices which appear in deficit states would provide enough profits to attract significant investment to ensure the optimal adequacy level in long term [16]. Therefore, this phenomenon is relevant and should be taken into account. However, most current methodologies for evaluating investments in the transmission system omit its consideration [2], [17].

The two-state model, illustrated in Fig. 1, incorporates most of the issues discussed above and is sufficient for the purposes of this article.

In this figure, **O** represents the operation state and **F** the failure state, λ is the failure rate and μ is the repair rate.

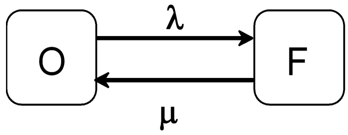

Fig. 1. Two-state model of electric system component

The steady state probabilities of operation and failure can be derived from these parameters according to [18]:

$$\Pr(\mathrm{O}) = \frac{\mu}{\mu + \lambda}; \; \Pr(\mathrm{F}) = \frac{\lambda}{\mu + \lambda} \quad (16)$$

Assuming, as is typical in reliability studies, that the transition between states in the two-state model can be described by a Markov process, the random Time To Failure (TTF) and Time To Repair (TTR) are distributed according to exponential distributions with constant parameters equal to μ and λ respectively. These times can be simulated in a chronological way through random and independent samples:

$$\mathrm{TTF} = -\frac{1}{\lambda}\left(\mathrm{U}[0,1]\right); \; \mathrm{TTR} = -\frac{1}{\mu}\left(\mathrm{U}[0,1]\right) \quad (17)$$

where U [0,1] are independent random numbers uniformly distributed in the interval [0,1].

Subsequently, in this module are performed optimal power flow (OPF) calculations, in order to determine the minimal operation cost on each hour of the planning horizon under the base and the investment scenario. The cost difference between both scenarios defines the underlying asset (the incremental social welfare) which is assessed in the next module.

The OPF is calculated using the power system simulation software Matpower 3.2 [19], modified to introduce FACTS devices in the transmission system. These FACTS devices are implemented according to the mathematical model which is exposed below.

Model of the FACTS devices: In this article, a Thyristors Controlled Series Compensator (TCSC) is analyzed. Its mathematical model is developed based on its operation in steady state. 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. The rating of TCSC is depending on the reactance and current capacity of the transmission line where the TCSC is located:

$$X_{ij} = X_{Line} + X_{TCSC}; \quad X_{TCSC} = r_{TCSC}.X_{Line} \qquad (18)$$

where X_{Line} is the reactance of the transmission line and r_{tcsc} is the coefficient which represents the degree of compensation by TCSC [20].

To avoid overcompensation, the working range of the TCSC is chosen between $-0.7X_{Line}$ and $0.2\ X_{Line}$. Moreover, it is considered 12% enhanced capacity in the line where the TCSC is connected due to the stability improvement.

B. Financial analysis module:

This module evaluates the present value of the incremental social welfare (ISW) on the basis of the incremental cost calculated in the previous module.

At first, the cash flows of the ISW, generated by the investment execution, is discounted by the financial cost of the investment (*WACC*, Weight Average Cost of Capital), according to the following expression:

$$PV\left(ISW_{s,k,j}\right) = \sum_{i=k}^{T}\left(\frac{ISW_{s,k,j}(i)}{(1+WACC)^i}\right); \qquad (19)$$
$$ISW_{s,k,j}(i) = \sum_{h=1}^{8760}\left(C_{i,h,j,base} - C_{s,i,h,j,inv}\right)$$

where $C_{i,h,j,base}$ and $C_{i,h,j,inv}$ are the costs of the operation for base case and investment case respectively, $ISW_{s,k,j}$ (*i*) is the incremental social benefit, $ISW_{s,k,j}$ is the present value of the *ISW* executing the portfolio investment in year *k* and *T* the investment term. In each case, the variables correspond to the *h*-th hour, *i*-th year, *j*-th realization of the Monte Carlo simulation of power system operation and the *s*-th investment strategy respectively.

Afterwards, considering *PV* ($ISW_{s,k,j}$) as the underlying asset, the ROV is applied in order to evaluate the strategic flexibility embedded in both investment alternatives, i.e. the postponement option in traditional transmission expansions and the FACTS-related options in those cases where the investment project include these controllers. Finally, risk-yield indices are utilized to identify the efficient investment portfolio.

In order to explain the evaluation procedure, for sake of simplicity, it is assumed two expansion alternatives: a FACTS devices and a transmission line (LT), these alternatives remain open for *M* years. Thus, the decision that the investor should take is:

- To invest in the FACTS devices first,
- To invest in the Line device first or,
- To invest in the FACTS and Line jointly.

These possibilities are mutually exclusive options, with a maturity of *M* years.

Note that it is possible to initially invest in any of the first two options and then in successive years prior to the expiration of the option, invest in the other. This means that the execution of any of the two alternatives (FACTS or line) separately creates the option of investing in the other alternative afterwards. This is the flexibility of investment in stages and must be considered in the assessment.

Additionally, the FACTS alternative has the option of abandon, which allows the investor to sell the devices at its scrap value.

Below are exposed Bellman equations for the evaluation of the options:

Option to invest first in the FACTS:

$$F_F(t_n, X_{t_n}) = \max\left\{\begin{array}{l}\Pi_F\left(t_n, X_{t_n}\right)...\\ +\max\left(F_{Ab}(t_n, X_{t_n}); F_{LT}^F(t_n, X_{t_n})\right);...\\ \mathrm{E}_{t_n}^*\left[F_F\left(t_{n+1}, X_{t_{n+1}}\right)\right].df\end{array}\right\} \qquad (20)$$

Option to invest first in the LT:

$$F_{LT}(t_n, X_{t_n}) = \max\left\{\begin{array}{l}\Pi_{LT}\left(t_n, X_{t_n}\right) + F_F^{LT}(t_n, X_{t_n});...\\ \mathrm{E}_{t_n}^*\left[F_{LT}\left(t_{n+1}, X_{t_{n+1}}\right)\right].df\end{array}\right\} \qquad (21)$$

Option to invest in the FACTS & LT jointly:

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

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, both for the option *m* (*F*: FACTS, *LT*: line transmission, *Ab*: FACTS Abandon) at the state *n* (*F*: FACTS investment done, *LT*: Line investment done, *Ab*: FACTS Abandon done).

Developing the equation (20):

$$F_{Ab}(t_n, X_{t_n}) = \max\left\{\begin{array}{l}\Pi_{Ab}\left(t_n, X_{t_n}\right) + F_{LT}^{Ab}(t_n, X_{t_n});...\\ \mathrm{E}_{t_n}^*\left[F_{Ab}\left(t_{n+1}, X_{t_{n+1}}\right)\right].df\end{array}\right\} \qquad (23)$$

$$F_{LT}^{Ab}(t_n, X_{t_n}) = \max\left\{\begin{array}{l}\Pi_{LT}^{Ab}\left(t_n, X_{t_n}\right);\\ \mathrm{E}_{t_n}^*\left[F_{LT}^{Ab}\left(t_{n+1}, X_{t_{n+1}}\right)\right].df\end{array}\right\} \qquad (24)$$

In the same way, developing the equation (21) y (22):

$$F_F^{LT}(t_n, X_{t_n}) = \max\left\{\begin{array}{l}\Pi_F^{LT}\left(t_n, X_{t_n}\right) + F_{Ab}^{LT\&F}(t_n, X_{t_n});...\\ \mathrm{E}_{t_n}^*\left[F_F^{LT}\left(t_{n+1}, X_{t_{n+1}}\right)\right].df\end{array}\right\} \qquad (25)$$

$$F_{Ab}^{LT\&F}(t_n, X_{t_n}) = \max\left\{\begin{array}{l}\Pi_{Ab}^{LT\&F}\left(t_n, X_{t_n}\right);...\\ \mathrm{E}_{t_n}^*\left[F_{Ab}^{LT\&F}\left(t_{n+1}, X_{t_{n+1}}\right)\right].df\end{array}\right\} \qquad (26)$$

In all cases:

$$\Pi_m^n(t_n, X_{t_n}) = PV\left(ISW_{s,k,j}\right) - I_{s,k} \qquad (27)$$

where $I_{s,k}$ is the investment cost of the s-th strategy at the k-th year.

For solving these real option problems, the LSM approach is applied and the value of the options available is calculated.

It can be noted that the flexibility added by the FACTS appears only when the investment is executed and its strategic flexibility is available after the investment expenditure has been realized. For this reason, these options reinforce the investment signal of immediate execution. Thus, the alternatives with FACTS allow making investment in stages, retaining flexibility for managing uncertainties during the whole planning horizon.

On the contrary, in alternatives where these options are not available (only the deferring option is present), the huge volatility of the investment performance and the fact that the flexibility is lost in the moment of the investment execution increase the value of the postponement option. This suggests that planners should "wait and see" until a substantial portion of the uncertainty is resolved.

Following, a detailed numerical example built on an actual setting, demonstrates the importance of considering the value of flexibility when assessing transmission investments.

VI. Valuing Flexible Investment Expansion. Numerical Example

For the sake of clearness the proposed approach is tested into a simple test system of three areas, represented by three nodes, connected by three transmission interconnections. In this test system two investment alternatives are evaluated; alternative 1: new 220 kV LT of 190 km and 150 MW of capacity between nodes 1 and 3, alternative 2: a TCSC of +115/-30 MVAr connected in serie with the LT between nodes 1 and 3. The test system summarized above is shown in Figure 2.

Then, there are three mutually exclusive options (strategies), which must be evaluated:

- to invest in the FACTS devices first (S1),
- to invest in the Line device first (S2) or,
- to invest in the FACTS and Line jointly (S3),

In Table I, reliability parameters of system component are given, as they are necessary for taking into account their availability in the investment evaluation.

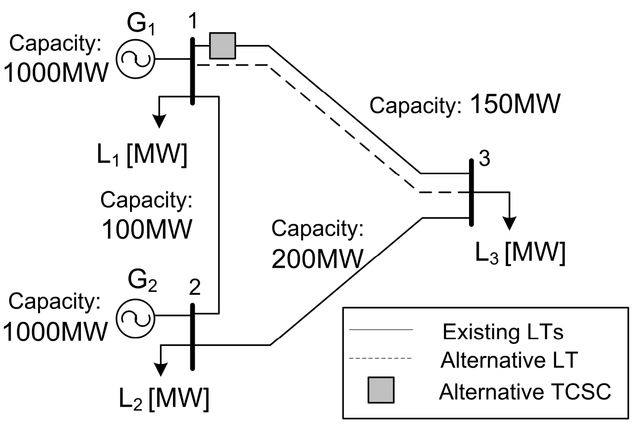

Fig. 2. Test System and investment alternatives.

TABLE I
RELIABILITY PARAMETERS OF SYSTEM COMPONENTS

Parameter	Generators	Line	TCSC
λ [1/h]	0.005	0.00026	1.079x10-5
μ [1/h]	0.0495	0.0909	0.0167

Table II provides the generators parameters needed for performing the generation cost evolution over the investment horizon.

TABLE II
GENERATOR COST PARAMETERS

Generator	a0	a1	a2	$p^F(0)$	$\overline{p^F}$	σ^{p^F}
G1	120	8.9	0.0015	1.50	1.34	0.16
G2	150	7.2	0.0014	1.65	1.34	0.16

The load duration curves of each load remain constant over the planning period and it has been discretized as illustrated in Table III. As well probabilistic parameters for simulating its annual growth are exposed.

TABLE III
DURATION AND GROWTH PARAMETERS OF DEMAND

Load	L_1	L_2	L_3	Dur.	R(0)	σ
Peak	110	95	180	8 hs	5%	2%
Base	180	70	115	16 hs	2%	0.8%

Moreover, loads have the following matrix correlation:

$$\Theta_{pico} = \begin{bmatrix} 1 & 0.4 & 0.2 \\ 0.4 & 1 & 0.55 \\ 0.2 & 0.55 & 1 \end{bmatrix}; \quad \Theta_{base} = \begin{bmatrix} 1 & 0.3 & 0.7 \\ 0.3 & 1 & 0.8 \\ 0.7 & 0.8 & 1 \end{bmatrix}$$

Costs of transmission lines have been modeled as a linear function of the LT capacity, as indicated in Table IV.

TABLE IV
TRANSMISSION LINES INVESTMENT COSTS.

Voltage	Fixed Costs \$/km	Capacity Costs \$/(MW·km)
220 kV single circuit	90.000	800

The initial investment including installation costs for the TCSC per MVAr are approximated similar to what is proposed in [20] and [21] using the equation:

$$I_{\text{TCSC,MVar}} = 182 \frac{\text{k\$}}{\text{MVar}} - 450 \frac{\$}{\text{MVar}^2}.S + 0.5 \frac{\$}{\text{MVar}^3}.S^2 \quad (28)$$

The total investment costs are:

$$I = I_{add} + I_{\text{TCSC}} = I_{adic} + S.I_{\text{TCSC,MVar}} \quad (29)$$

where S is the rating of the TCSC in MVAr and I_{add} is the additional investments for research, land, infrastructure and legal issues. In this case study this value is set to I_{add}=0.35I. Similarly, the scrap value of the FACTS devices is considered 0.40I.

Under energy deficit scenarios, the nodal price is set at the value of VOLL (Value of Lost Load), which has been assumed as 700 \$/MWh. It is considered as maturity of all investments options three years and 15 years as investment horizon. Lead construction time is assumed to be one year and discount rate is set to 12%/yr for all possible transmission projects.

The Monte Carlo stopping criterion is defined with a maximum relative error of 1,5% with a confidence interval of 95%, which is calculated according to the sequential estimation technique [15]. Hence, 1000 simulations were carried out in order to satisfy the convergence criterion. Below, the relative error as function of the number of realizations is shown in Fig. 2.

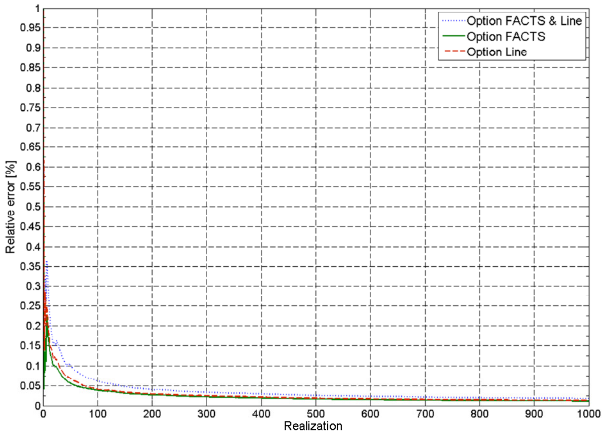

Fig. 2. Relative error of option values of each alternative.

Once stated these assumptions, the cited problem becomes a decision-making one which involves finding a sequences of transmission projects and flexible decisions by solving a real option problem according to the proposed framework (Eq. 20 to 22).

As a result of this analysis, it is determined that S_1 is the best decision, unlike the decision suggested by the traditional investment evaluation approach (NPV) S_2 (see Table V).

TABLE V
RANKING OF STRATEGIES BY APPLYING THE PROPOSED EVALUATION APPROACH

Strategy (unit)	**Expected Option Value** (M$)	**Expected NPV value** (M$)
S_1	25,24 (1st)	18,99 (2nd)
S_2	24,11 (2nd)	19,25 (1st)
S_3	21,28 (3rd)	16,86 (3rd)

From these results, the flexibility value of each investment strategy can be calculated according to the following expression [4] (See Table VI):

$$\text{Option Value} = \text{NPV} + \text{Flexibility value} \tag{30}$$

Taking the volatility of the option value of each investment strategy as a measure of its risk, the risk profile can be obtained applying yield/ risk indices. Thus, the efficient investment portfolios can be identified, i.e. those that maximize return at certain risk level.

This procedure utilizes the Sortino Ratio [23], which measures the risk-adjusted return of an investment asset, portfolio or strategy according to the following equation:

$$S = \frac{E[R] - MAR}{DR} \tag{31}$$

where $E[R]$ is the expected return of investment strategy, MAR is the minimum acceptable return and DR is the downside risk. The downside risk is characterized by the semi-standard deviation of return on investment that represents the deviation of returns that are lower than the MAR. Fig. 3(a) shows the probability distribution of the option values.

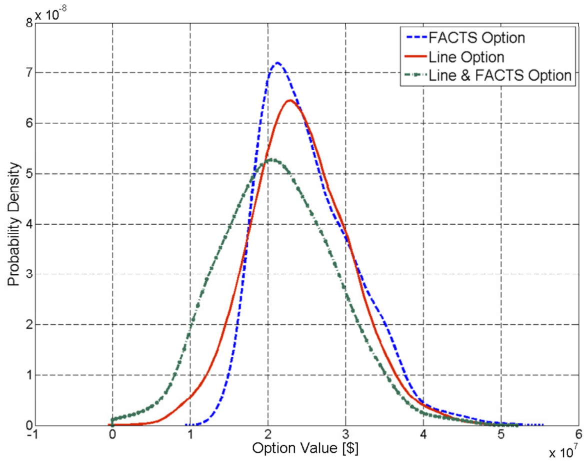

Fig. 3. Resulting Probability Distribution Functions of the expansion strategies

Risk profiles of the analyzed investment portfolios are exposed below in Table VI. It is fixed as the minimum accepted return, the expected NPV of the strategy 3, i.e. the minimum expected value of the strategies discussed.

TABLE VI
FLEXIBILITY VALUE FOR PROPOSED INVESTMENT STRATEGIES

Strategy (unit)	**Flexibility value** (M$)	**Sortino Ratio** (%)
S_1	6,25 (1st)	16.9135 (1st)
S_2	4,56 (2nd)	8.3351 (2nd)
S_3	4,42 (3rd)	4.2113 (3rd)

Table VI shows that the investment alternative with only the FACTS devices has a higher flexibility value than the other strategies. Similarly, S_1 has the best risk profile.

All this points out that - though the traditional investment appraisal (NPV) indicates S_2 as the optimal investment alternative- the optimal investment strategy taking into account the flexibility value is to invest first in FACTS devices. The strategic flexibility of FACTS remains after the investment expenditure has been realized and its operational flexibility reduce considerably the risk levels.

Thus, the investments in FACTS devices allow making investment in stages, retaining flexibility for managing uncertainties during the whole planning horizon.

On the contrary, in traditional alternatives (LT investments) these options are not available (only the deferring option is present). Then, the huge volatility of the investment performance (high risk level) and the fact that the flexibility is lost in the moment of the investment execution increase the value of the postponement option. This suggests that planners should “wait and see” until a substantial portion of the uncertainty is resolved.

VII. CONCLUSION

This paper shows a new framework for assessing flexible investment within the expansion transmission planning under uncertainties. Large uncertainties, inherent to electric power systems have been successfully modeled and managed in order to improve the investment risk profiles.

Traditional investment appraisal methods are typically inappropriate approaches when assessing transmission investments, since the presence of huge uncertainties dramatically increases the risk involved in irreversible large-scale decisions.

Thus, the assessment of flexibility in dealing with the uncertainties by executing available real options is a key task. The options derive their value from the fact that they establish a lower limit against possible project losses. In this sense, a real option valuation framework has been developed, using the novel LSM approach for solving the optimization problem.

Hence, it has been verified that flexible expansion plans and improved adaptability levels to the uncertain future scenarios can be obtained by strategically combining FACTS devices and conventional investments in transmission lines along the planning horizon. These expansion alternatives induce the investment execution in stages instead of only deferring large transmission line projects. An optimal tradeoff between large transmission expansion investments and flexibility offered by FACTS devices can be achieved, which could generate a progressive adaptation of the transmission system to the power market development.

Future research should be focused on properly assessing the impact of the relocalization options of the FACTS devices in the flexible expansion plans.

VIII. References

[1] S. Stoft, "Transmission Investment in a Deregulated Power Market," Competitive Electricity Markets and Sustainability, Edward Elgar Publishing Limited, edited by François Lévêque, chap. 4, pp. 87 – 130, 2005.

[2] G. Latorre, R.D. Cruz, J.M. Areiza and A. Villegas., "Classification and Publications and Models on Transmission Expansion Planning," IEEE Trans. Power Systems, vol. 18, pp. 938 – 946, May 2003.

[3] G. Blanco, F. Olsina and F. Garcés, "Dispositivos FACTS en Mercados Eléctricos Competitivos - Estado del Arte," in the VII Latin American Congress on Electricity Generation & Transmission, Paper C034 October 24-27 2007.

[4] S. Olafsson. "Making Decision under uncertainty – implication for high technology investment," *BT Journal*. Vol. 22 No.2, 2003.

[5] F. Longstaff and E. Schwartz, "Valuing American options by simulation: a simple least-squares approach," *The Review of Financial Studies*, vol. 14(1), pp. 113–47, 2001.

[6] A. Gamba, "Real Options Valuation: a Monte Carlo Approach," University of Verona, pp. 1-49, 2003.

[7] Kirschen D. and Strbac G, "Fundamenntals of Power Systems Economics," Ed. John Wiley & Sons, pp. 228 – 264, 2004.

[8] P. Vazquez and F. Olsina. "Valuing Flexibility of DG Investments in Transmission Expansion Planning," Power Tech Proceedings, 2007 IEEE Switzerland, Jul. 2007, pp. 1-6.

[9] S. Blumsack, "Network Topologies and Transmission Investment under Electric-Industry Restructuring," PhD Thesis, Carnegie Mellon University, 2006.

[10] G. Shrestha and P. Fonseka. "Flexible transmission and network reinforcements planning considering congestion alleviation," IEE Proc.-Gener. Transm. & Distrib., vol. 153, pp. 591- 598, Sep. 2006.

[11] R. Brosch. "Portfolio-aspects in real options management," Working paper series: finance & accounting, J.W. Goethe-University, No.61, ISSN1434-3401, February 2001.

[12] A. Rodrigues and M. Rocha, "The Valuation of Real Options with the Least Squares Monte Carlo Simulation Method," Management Research Unit, University of Minho, Portugal, Feb. 2006.

A. Dixit and R Pindyck, *Investment under Uncertainty*, Princeton University Press, pp. 93-125, 1994.

[13] G. Cortazar, M. *Gravet and J. Urzua, "The v*aluation of multidimensional American real option using the LSM simulation method," *Computers & Operations Research,* vol. 35, pp. 113-129, Jan. 2008.

[14] M. Nelson and O. Añó, "Modelación del Precio Spot Hidrotérmico," presented at the XII Encuentro Regional Iberoamericano del CIGRÉ, May 2007.

[15] F. Olsina, C. Larisson and F. Garcés, "Análisis de Incertidumbres en Sistemas Hidrotérmicos de Generación a través de Simulación Estocástica," presented at the VII Latin American Congress on Electricity Generation & Transmisión, 2007.

[16] G. Blanco, O. Ojeda, F. Olsina and F. Garcés "Análisis de incertidumbres en el desempeño de inversiones en la red de transporte a través simulación estocástica," presented at the XIII Encuentro Regional Iberoamericano del CIGRÉ, May 2009.

[17] R. Billinton and R.Allan, *Reliability Evaluation of Power Systems*, Plenum Press, New York, 1996.

[18] R. D. Zimmermann, C. Murillo-Sánchez and D. Gan, "Matpower a Matlab power system simulation package" User´s Manual 3.2, av. online en http://www.pserc.cornell.edu/matpower/manual.pdf, 2007.

[19] Cai L., Erlich I., y Stamtsis G. "Optimal choice and allocation of FACTS devices in deregulated electricity market using genetic algorithms," in *Power Systems Conference and Exposition, 2004. IEEE PES*, vol.1, pp. 201- 207, Oct. 2004.

[20] C. Schaffner and G. Andersson, "Determining the value of controllable devices in a liberalized electricity market: a new approach," in *Power Tech Conference Proceedings,* 2003 IEEE Bologna, vol. 4, pp. 1-7, Jun. 2003.

[21] G. Fishman, *Monte Carlo: Concept, Algorithms and Applications*, vol I. New York: Springer 1996, pp. 21-120.

[22] A. Chaudhry and H. Johnson, "The Efficacy of the Sortino Ratio and Other Benchmarked Performance Measures Under Skewed Return Distributions," *Australian Journal of Management*, Vol. 32, No. 3, Special Issue, March 2008.

IX. Biographies

Gerardo A. Blanco (SM'08) obtained the Electromechanical Engineer degree from the National University of Asunción, Paraguay in 2004. From 2003-2005 he was with Administration National of Electricity (ANDE) in Paraguay, at Operation Power System Department. Currently he is working toward a Ph.D degree at Institute of Electrical Energy (IEE), National University of San Juan (UNSJ). He is actually visiting research at the Institute of Power System and Power Economics of the Technical University of Dortmund, Germany. His research interests are power investment under uncertainty, risk management and FACTS devices in power markets.

Fernando G. Olsina obtained the Mechanical Engineering degree in 2000 from National University of San Juan (UNSJ) and the Ph.D. degree in Electrical Engineering in 2005 from the Institute of Electrical Energy (IEE), Argentina. He was visiting researcher at the Institute of Power System and Power Economics (IAEW) of the Aachen University of Technology (RWTH), Germany. His research interests focus on long-term power market modeling, power investments under uncertainty and reliability & risk management.

Osvaldo A. Ojeda obtained the Electrical Engineering degree in 2002 from the National University of San Juan (UNSJ), Argentina and the PhD. degree in Electrical Engineering in 2007 from the Institute of Electrical Energy at the UNSJ. He was visiting researcher at the Bremer Energie Institut in Bremen, Germany from 2005 to 2007. His research interests include power system interconnections, modeling of electricity markets.

Francisco F. Garcés obtained the Electromechanical Engineering degree from the University of Cuyo, Argentina, in 1974 and the Dr.-Ing. degree from the Aachen University of Technology (RWTH), Federal Republic of Germany, in 1982. Presently is a Vice-Director of the Institute of Electrical Energy (IEE), National University of San Juan, Argentina and Head of the Reliability & Risk Management Group. His main research interests are power system reliability and reserve calculations.