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Real option valuation of power transmission investments by stochastic simulation

Rolando Pringles *, Fernando Olsina, Francisco Garcés

National Scientific and Technical Research Council (CONICET), Av. Rivadavia 1917, C1033AAJ Buenos Aires, Argentina
Institute of Electrical Energy (IEE), National University of San Juan (UNSJ), Av. Lib. Gral. San Martín 1109(O), J5400ARL San Juan, Argentina

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ABSTRACT

Network expansions in power markets usually lead to investment decisions subject to substantial irreversibility and uncertainty. Hence, investors need valuing the flexibility to change decisions as uncertainty unfolds progressively. Real option analysis is an advanced valuation technique that enables planners to take advantage of market opportunities while preventing or mitigating losses if future conditions evolve unfavorably. In the past, many approaches for valuing real options have been developed. However, applying these methods to value transmission projects is often inappropriate as revenue cash flows are path-dependent and affected by a myriad of uncertain variables. In this work, a valuation technique based on stochastic simulation and recursive dynamic programming, called Least-Square Monte Carlo, is applied to properly value the deferral option in a transmission investment. The effect of option's maturity, the initial outlay and the capital cost upon the value of the postponement option is investigated. Finally, sensitivity analysis determines optimal decision regions to execute, postpone or reject the investment projects.

1. Introduction

In the last decades, the global electric power industry has faced large and paradigmatic structural changes. The power transmission sector suffered a major shift, mainly in how system expansions are planned and implemented. In the traditional vertically integrated electricity industry, centralized planning of transmission expansions is coordinated with generation system planning. In current competitive markets, expansion of transmission infrastructure has been decoupled of the generation planning, making difficult investment coordination. Consequently, transmission investment decisions are undertaken by transmission network owner or outside investors based on expectations of future development of the generation system and consumption.

Different regulatory framework approaches for planning and expansion of electricity networks have been proposed in the context of electricity markets, from approaches based on regulatory incentives (Oren et al., 2002; Vogelsang, 2006) to fully liberalized mechanisms, in which private investors evaluate different projects and invest at own risk (Hogan, 2003; Kristiansen and Rosellón, 2006). Although there is significant progress in each of these proposals, including schemes of mixed regulatory frameworks (Hogan et al., 2010), the problem of transmission system expansion in electricity markets has not yet been satisfactorily solved. As a consequence, power markets often show problems of congestion, market power, high energy prices and decreased levels of supply reliability (Joskow, 2005). In addition, the changes in the electricity industry increased in the uncertainty of key variables involved in expansion planning and valuation of investments. This uncertainty is a consequence of decentralization of decision making and asset operation, limited exchange of information between players, and lack of knowledge on long-term plans of market participants.

In the context of competitive markets, the investors are more interested in returns on short-term investments and are reluctant to get committed in transmission expansions that require earlier large outlays and long payback periods. The reason is that in the long term there is much more uncertainty about generation expansion, electricity demand growth and regulatory framework.

The current development of theoretical models and tools for transmission expansion planning is still below of practical needs posed by electricity markets. A main challenge is to value flexibility and dynamic

* Corresponding author at: Tel.: +54 264 4226444; fax: +54 264 4210299.
E-mail address: rpringles@iee.unsj.edu.ar (R. Pringles).

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adaptability in the context of planning under substantial uncertainty (Latorre et al., 2003; Rosellón, 2003; Wu et al., 2006).

The financial viability of investment projects or the selection of investment alternatives is typically assessed by cost–benefit analysis. The most widely used method is updating the future cash flows generated by the project. This method is often referred as Discounted Cash Flow (DCF). DCF-based techniques allow summarizing the economic performance of complex large-scale investment projects in a single metric, such as the net present value (NPV). In order to address uncertainty on project variables, the assessment methodology commonly indicates to perform sensitivity analysis, analyze different scenarios, or get the probability distribution of the project value through Monte Carlo simulations.

Even though these attempts are useful to incorporate uncertainty into decision making, they do not solve the natural limitations of the DCF methodology. Indeed, the inherent flexibility embedded into most investment projects is not accounted for by traditional appraisal methods. It has been shown that the NPV rule often leads to suboptimal decisions when irreversible investments are subjected to uncertainty and investors have flexibility into decision making (Dixit and Pindyck, 1994; Mun, 2006; Trigeorgis, 1996).

In uncertain environments, managerial flexibility has a significant economic value. Methods that recognize the monetary value of the options embedded in investment opportunities have been developed in the past. In order to quantify the monetary value of flexibility, the consequences of future decisions contingent up on unfolding uncertainties must be assessed. This paradigm is called contingent decision making.

Contingent investment decisions can be evaluated with Decision Tree Analysis (DTA) technique. The potential of DTA is reflected when the uncertainty affects sequential investments that resolve in different times. However, DTA has important limitations that make it unfeasible for a proper assessment of many investment projects. These problems are the curse of dimensionality and the use of a constant risk-adjusted discount rate. Using a constant discount rate is wrong because in each decision point the earlier uncertainty is resolved and the risk level of the project is modified (Mun, 2006).

An emerging paradigm called real option analysis (ROA) has proved to be a powerful approach for addressing contingent decision making. This is an adaptation of financial options analysis applied to valuing of physical or real assets. The ROA assesses the implied value of flexibility that is embedded in many investment projects (Amram and Kulatilaka, 1999). Flexibility acknowledges that investment plans are modified or deferred in response to the arrival of new (though never complete) information or until the uncertainty is fully resolved. Under this approach, the investor is able to take advantage of new opportunities while mitigating or preventing losses in a timely manner.

The advent of liberalized electricity industry has created a suitable space for development and implementation for real option analysis. This is mainly because the investments in power infrastructure are partially or fully irreversible, affected by several uncertainties and with flexibility in making investment decisions.

Real options have been successfully applied to generation projects considering different types of options and uncertainties. Flexible investments in nuclear power plants, hydroelectric plants and renewable energy projects have been evaluated by real option analysis (Caminha et al., 2006, Gollier et al., 2005, Kiriyama and Suzuki, 2004). Besides, real options are used in selecting generation technologies and in optimal scheduling of multi-fuel power plants (Botterud et al., 2005; Murto and Nesse, 2002; Näsäkkälä and Fleten, 2005, Sekar, 2005).

However, the development of real options for valuing investments in the transmission system has been much more limited. In recent years, the importance of this technique has been shown and some important progress has been achieved.

The early works deal with the investment transmission problems as an optimal stopping problem. These works incorporate the uncertainties in demand, regulatory process and congestion-rent among others (Ocampo-Tan and Garcia, 2004; Saphores et al., 2002). Simple analytical frameworks to evaluate flexible investment decisions in transmission infrastructure are proposed in Saphores et al. (2002) and Boyle et al. (2006). The great potential of real option analysis to evaluate power transmission investments is described in a few theoretical works (Hedman et al., 2005; Ramanathan and Varadan, 2006). The findings highlight the superiority of real options in deregulated markets, encouraging experts in the field to show companies and practitioners the value of this approach (Wijnia and Herder, 2005). Besides, assessments of flexibility in network investments considering flexible distributed generation and FACTS have been proposed (Blanco et al., 2011a; Vazquez and Olsina, 2007). The results indicate that flexible alternatives are often preferred to conventional expansion projects. Finally, real option analysis was used to design regulatory frameworks for the expansion of transmission systems (Pringles et al., 2014).

Even though there is a great interest in applying real option analysis for appraising transmission network investments, the published literature reveals the lack of methodologies to properly perform this task. The early state of the field causes many conceptual mistakes and inappropriate assumptions in the application to power systems, mainly because the electricity market operates under physical laws and uncertainties are very different from markets with experience in real option applications.

The objective of this work is to provide a framework capable of correctly evaluating power transmission investments in competitive electricity markets under conditions of uncertainties and strategic flexibility. Options embedded in transmission investment projects are valued by a stochastic simulation method. Simulation methods enable to successfully capture the characteristics of investments in transmission system (i.e. path-dependent returns and investments that can be executed at any time). The remainder of this article is organized as follows. In the next section, the fundamentals of real option analysis are summarized. The advantage of simulative techniques over other valuation methods is highlighted. The stochastic simulation method for assessing the value of flexible investments under uncertainty is described in Section 3 and a framework for evaluating investments in the electric power transmission is proposed. Section 4 presents an example of transmission investment valued with ROA. Numerical results and sensitivity analysis on an example case for demonstrating the practicability of the proposed valuation method are provided. Finally, Section 5 draws the conclusions of the research.

2. Background

2.1. Investment valuation under uncertainty and managerial flexibility

Currently, the electricity markets require strategic investment decisions in an environment of increasing uncertainty, where future market conditions, development costs and behavior of competitors are highly uncertain.

Typically, managers anticipate and respond to uncertainty by making corrections on the project implementation, invest in stages, abandon projects, and acquire licenses or patents among others. In modern language, managers are making contingent decisions, i.e. decisions to invest or disinvest that depend on the development of events. This illustrates that project managers often intuitively are aware about the existence of options on assets, but they lack of formal decision tools to properly value flexibility.

The presence of flexibility or real options may drastically increases the economic value of investment projects. The value of a project with flexibility is determined as the value of project without options using the traditional NPV plus the economic value of the options:

$$\begin{aligned} NPV_{\text{flexible}} = \; & NPV_{\text{classic}} \\ & + \text{Value of flexibility (value of real options)}. \end{aligned} \tag{1}$$

In contrast to classical theory of valuation (DCF) that considers management as a passive actor, real options deem management as an active entity able to take advantage of opportunities emerging during the development of businesses, envisaged previously by strategic investments. Additionally, real options recognize the ability of the management to limit losses without losing the capacity to capture additional profits if the opportunity arises.

2.2. Real option analysis

Real option analysis is a conceptual extension of financial option theory applied to real or physical assets. The main feature of financial options theory is that financial assets are valued under uncertainty. While financial options are written in explicit contracts, real options need to be first recognized and identified, and conceptually specified.

A financial option is a security that grants its owner the right, but not the obligation, to buy/sell a financial asset at a specified period of time in exchange of a certain amount of money. Analogously, a company that makes strategic investments has the right, but not the obligation, to take advantage of emerging opportunities in the future. Accordingly, a strategic investment opportunity can be considered as a source of cash flows plus a set of options in exchange of an initial outlay. Consequently, an investor in a flexible project, like a financial option holder, is protected against losses, while the ability to capture opportunities is not deteriorated.

The real options are embedded in plans, projects, actions or flexible business investments. A real option is for instance the ability to postpone an investment awaiting for arrival of key information; abandon or sell the assets if the results are adverse; change the input, the output or technology in response to market conditions; expand the production capacity or the operational scale of the project if conditions are favorable; and oppositely reduce the size of operations if the market conditions are unfavorable.

n order to consider various real options in an investment project, options can be combined sequentially or in compound manner. As a result, in each of these cases a project with options has an additional value with regard to a static project. This value is precisely that seeks to determine the ROA.

2.3. Valuation methods of real options

The methods for real option valuation derive from models for appraising financial options. When valuing real options, compliance with the mathematical assumptions established for financial assets cannot always be ensured. There are three general methods for solving the valuation problem, but its applicability in the real option field is conditional upon the specific characteristics of each problem. These methods are stochastic differential equations, dynamic programming and simulation models.

Under specific conditions, the dynamics of the option value is analytically described by a stochastic partial differential equation (PDE). The analytical solution of the PDE provides the value of the option as a direct function of inputs. The best-known analytical solution, which constitutes the seminal work on option valuation theory, is the Black–Scholes equation (Black and Scholes, 1973).

Dynamic programming is an approach based on splitting the whole problem into two basic components: the immediate decision and a continuation function that summarizes the consequences of all future subsequent decisions starting from the decision time. The optimal exercise time for the option is based on the Bellman's principle of optimality. The problem is solved by backward induction. The most important method based on dynamic programming is the binomial lattice (Cox et al., 1979).

Last, simulation models consider thousands of likely paths of underlying asset evolution generated by Monte Carlo sampling from now until maturity date of the option. For each path, the optimal investment strategy is determined and the option return is calculated. The value of the option is estimated as the average of the present value of returns for all paths.

Monte Carlo technique increases the complexity in calculating the option value. By its own nature, simulation has however significant advantages over closed-form solution models, such as Black–Scholes and traditional binomial tree techniques. The Monte Carlo method allow modeling multiple underlying assets and correlation between cash flows of different sources as well as considering multiple sources of uncertainty and different kinds of stochastic behavior of uncertain variables. Additionally, stochastic simulation enables valuing of compound options and options with complex features, such as path-dependent or American options. Finally, simulation models are amenable to distributed computing techniques in order to drastically reduce the computation time.

In order to value American options, simulation methods combine traditional techniques, such as Monte Carlo, introduced in finance by Boyle (1977), with dynamic programming (Barraquand and Martineau, 1995; Broadie and Glasserman, 1997). Longstaff and Schwartz (2001) have developed a novel valuation approach for American options called Least-Squares Monte Carlo (LSMC). The least-squares regression method is proposed to estimate the value of the optimal exercise function of the recurrence relation in the context of the dynamic programming problem. The result of least-square regression is an efficient unbiased estimator of the conditional expectation function and allows accurately estimating the optimal stopping-rule for the option. The LSMC method has advantages over other proposed simulation techniques: it is a simple method, requires less computational time, and can be applied for valuing complex and compound options with many underlying stochastic variables.

3. Methodology

3.1. The Least-Square Monte Carlo valuation algorithm

The problem of determining the value of an American option is an optimal stopping problem which is solved by the mean of dynamic programming. The computation of the conditional expectation function involved in the dynamic programming constitutes the main difficulty in the development of Monte Carlo technique. The main idea of LSMC algorithm is to approximate the continuation value in the Bellman equation using least-squares regression of expected returns conditional to the current value of state variables. The key is the use of statistical linear regressions for estimating the optimal exercise function. This considerably lessens the computational problem usually present in simulative models. Then, the optimal stopping time of the contingent right is determined from the continuation value. Finally, the value of the option can be estimated.

The LSMC method is not only efficient to value American financial options, but also can be extended to valuing complex real investments with several embedded real options and multiple uncertain state variables (Abdel Sabour and Poulin, 2006). LSMC approach has been successfully applied in various fields of industry, including the valuation of real options associated with patents, R&D projects (Schwartz, 2004), internet companies (Schwartz and Moon, 2001) and pharmaceutical companies (León and Piñeiro, 2004).

The use of the LSMC method to assess real options in power investments is indeed a very recent development. The review of literature in the field reflects a still very limited use of this assessment tool. In the power generation sector, the LSMC method is applied by Abadie and Chamorro (2009), Zhu and Fan (2011) and Zhu (2012). In the assessment of power transmission investments, LSMC has been used to valuing investments in flexible AC transmission devices (FACTS) (Blanco et al., 2011a; Blanco et al., 2011b; Tian et al., 2012).

The objective of LSM is to provide an approximate path to the optimal stopping rule that maximizes the value of an American option. The analysis of problem focuses on the case that American options can be exercised at N discrete times $0 < t_1 \leq t_2 \leq \ldots \leq t_N = T$, where T is the maturity date of the option. The continuous value of American option can be approximated considering N large enough.

The assessment begins generating a number of paths, w, which replicates the stochastic dynamics of the state variables (X) that determine the option value. The LSMC goal is to provide an exercise rule that maximizes the value of the option at each time step along each simulated path. The evaluation process begins from the maturity date and recursively progresses backward until time $t = 0$.

At maturity date, the value of underlying asset and the exercising value of the option are compared. The optimal exercise strategy for call options is to exercise if the value of underlying asset is greater than the exercise value. In this case is said that the option *is in the money*. When the underlying asset is less than the exercise value, the option will expire without being exercised. In this case is said that the call option *is out-of-the-money*. The value of a call option is given by the following expression:

$$F(T, w) = \max[S(T, w) - K, \ 0] \tag{2}$$

where $F(T, w)$ is the value of call option at time T for path w, $S(T, w)$ is the value of the underlying asset at time T for path w and K represents exercise value of the option.

In time t_i, previous to expiration date, the optimal strategy arises from comparing the immediate exercise value (future cash flows by exercising the option) with the expected cash flows from continuing (keep alive the option). If the immediate exercise value is positive and greater than the conditional expected value from continuing, $\Phi(t_i, w)$, the optimal decision is exercise the option:

$$F(t_i, w) = \max[S(t_i, w) - K, \Phi(t_i, w)]. \tag{3}$$

The arbitrage-free valuation theory implies that the value of continuing, or equivalently, the value of the option assuming it has not been exercised before the time t_i, is given by the expectation of cash flows generated by the option $F(j, t_{i+1}, T, w)$ discounted with respect to a risk-free measure Q, where r is the risk-free discount rate, and for which the holder follows an optimal stopping strategy for all j, with $t_{i+1} \le j \le T$:

$$\Phi(t_i, w) = (1+r)^{-(t_{i+1}-t_i)} \mathbb{E}_Q\left[F(j, t_{i+1}, T, w)\right]. \tag{4}$$

The option value is maximized along the path if the investor exercises as soon as the immediate exercise value is greater than or equal to the value of continuing. Thus, the key to optimally exercising an American option is to estimate the continuation value, being this the central difficulty of the method.

The LSMC approach uses least-squares regression to approximate the conditional expectation of the continuation function at each time t_i. The conditional expectation can be represented as a linear combination of a countable set of orthonormal basis functions $\{L_m\}$:

$$\Phi(t, w) = \sum_{m=1}^{\infty} \phi_m(t) L_m(t, X). \tag{5}$$

Generally, the chosen functions are Hermite, Legendre, Chebyshev and Jacobi polynomials, Fourier series and power series (Longstaff and Schwartz, 2001).

The values of $\phi_m(t)$ are estimated by least-squares regression of $\Phi_M(t, X)$ with $M < \infty$ basis functions elements:

$$\left\{\hat{\phi}_m(t_i)\right\}_{m=1}^{M} = \arg\min_{\left\{\phi_{m=1}^{M}\right\}} \left\| \sum_{m=1}^{M} \phi_m(t_i) L_m(t_i, X) - \sum_{k=i+1}^{N} (1+r)^{-(t_k - t_i)} F(j, t_{i+1}, T, \cdot) \right\| \tag{6}$$

where $\|\cdot\|$ is the norm of the Hilbert space, L^2.

As result, the estimated value of the continuation function is:

$$\hat{\Phi}_M(t_i, w) = \sum_{m=1}^{M} \hat{\phi}_m(t_i) L_m(t_i, X). \tag{7}$$

The value of the continuation function is estimated only for the paths where the option is in the money, because only these paths are relevant in the decision to exercise the option. Thus, the region over which the conditional expectation must be estimated is limited. This decreases the number of basis functions needed to obtain a good approximation of the continuation function.

Once the function is estimated $\hat{\Phi}_M(t_i, w)$ at time t_i, it can be determined whether exercising the option is optimal or not. Then, the optimal exercise time $\tau(w)$ in each instant of time t_i takes place if the following condition holds:

$$[S(t_i, w) - K] \ge \hat{\Phi}_M(t_i, w). \tag{8}$$

Once identified the optimal exercise decision for instant t_i over all w paths, it is possible to determine the continuation function for t_{i-1} by the expected cash flow of the option $\mathbb{E}[F(j, t_i, T, w)]$. In this way, the recursive process continues repeating the procedure until all exercise-decisions along each simulated paths w are determined.

Finally, the estimated value of the option is obtained by discounting the cash flow resulting from the optimal exercise of the options backward at the moment $t = 0$, to the risk-free rate and taking the average over all paths w, including those paths that are out of the money, i.e. those with zero value. Fig. 1 shows schematically the option evaluation procedure by applying the LSMC approach.

$$F = \frac{1}{W} \sum_{w=1}^{W} (1+r)^{\tau(w)} F(\tau, w). \tag{9}$$

3.2. Analysis of valuation results considering real options

The analysis of results allows defining optimal decision policies on the real options embedded in investment projects. Through option analysis, the parameters and reference models that investors must consider in order to make the right investment decisions are defined. Among them we can mention:

- *Net present value of the project with flexibility*. The flexible NPV indicates if the investment project considering the embedded options creates value for the investor. In this case, the value of embedded options must be assessed and depending on these values, the final strategy that the investor will take along the course of the investment project can be outlined.
- *Critical values for decision-making*. The critical value defines the threshold value that triggers action to make an optimal decision. In order to determine the critical values a sensitivity analysis of the value of real options is performed.
- *Optimal decision regions*. The decision regions determine the optimal investment strategies based on the value of different input parameters. These regions depend on the investment project and the embedded options.

If an investment project with the option to defer decision is valuated, decision regions are to invest immediately, postpone or refuse the investment project. For a project with a growth option, the decision regions are to invest considering expansion, invest without considering this flexibility or rejecting the project. In case of an abandon option, the regions are to invest considering the abandon option, invest without considering the option or refusing the investment project. The decision regions are defined according to conditions in the value of the project considering or not the flexibility and the value of embedded options, as shown in Table 1.

3.3. Real option analysis of power transmission investments

The implementation of the real option analysis is particularly suited to evaluate investment projects in transmission system expansions. This is because the transmission investments have the following conditions: the investments are partially or completely irreversible, there is substantial uncertainty about the future performance of the investments, the management has some flexibility regarding the opportunity for effectively carrying out the project, and it is possible to acquire new

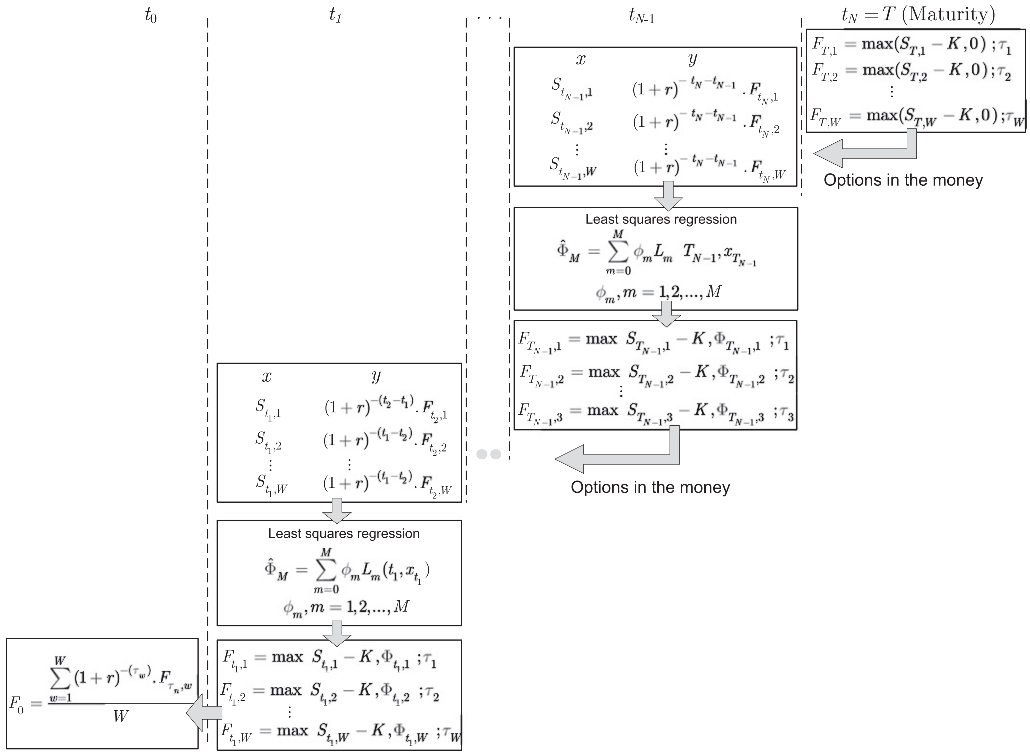

Fig. 1. Option valuation scheme by LSMC approach.

information about the future evolution of relevant variables, although this information may always be incomplete.

The following are a set of real options that can be considered when evaluating investments for the expansion of the transmission network.

- *Option to defer*: Provides the right to postpone the investment for a period of time, rejecting immediate cash flows, awaiting the arrival of new and better (though never complete) information. The option to postpone may reduce uncertainty about key variable that affects the development of the project or wait that improvement in driving variables takes place at the cost of the foregone revenues. In transmission investments, the option to defer is equivalent to postpone construction of a power line or some specific equipment to expand the transmission capacity.
- *Growth option*: If market conditions are better than expected, it provides the ability to expand production capacity or operational scale of a project, if previously an initial investment is made. An example of growth option can include a) to construct a transmission line with a physical structure suitable for a higher voltage level than the initial operation voltage level. If demand grows in the future, this strategy has the flexibility of expanding capacity by increasing the voltage level updating only some few components; b) to build a double-circuit electric power line, where firstly only one circuit is wired and the second circuit is built later if the circumstances look profitable, otherwise the second circuit is not installed.
- *Option to abandon*: If market conditions look unfavorable, flexibility allows inexpensively closing activities and liquidates the assets. This real option provides partial insurance against failure with an exercise price equal to sales value of the project. For instance, if the transmission investment is made under a merchant approach, the regulator can offer the flexibility to abandon this approach and migrate to the regulated rate of return approach whether market conditions are adverse.
- *Compound options*: Such options comprise two or more options. The exercise of the first option creates a new option, which if exercised it may again create further opportunities. A compound option may consist of an option to defer the initial investment in a transmission line and an option to expand the capacity if market conditions are favorable, or an option to leave the business in case the market conditions deteriorate.

In the following, example application of real options in a transmission project that considers the option to defer will be presented.

Table 1
Decision rules of flexible projects.

Option	Decision	Condition 1	Condition 2	Condition 3
Defer	Defer investment	NPV ≥ 0 NPV 0	Option > 0	$NPV_{flexible} > 0$
	Invest now	NPV ≥ 0	Option = 0	–
	Refuse investment	NPV < 0	Option > 0	$NPV_{flexible} < 0$
Expand or abandon	Invest considering options	NPV ≥ 0 NPV ≤ 0	Option > 0	$NPV_{flexible} > NPV$
	Invest without consider options	NPV ≥ 0	Option = 0	–
	Refuse investment	NPV < 0	Option > 0	$NPV_{flexible} < 0$

4. Results and discussions

4.1. Exemplary case: valuing the option to defer

This example case considers the valuation of an investment project that entails the construction of a high voltage transmission line that interconnects two isolated electric areas. The assessment considers the option to defer the investment. The benefits of real option analysis versus traditional appraisal tools, such as the NPV approach, are illustrated.

The investment project corresponds to a 500 kV line with a capacity of 980 MW. The length of transmission line is 350 km. The initial investment cost is 89.36 M$. Fig. 2 illustrates the interconnection of both power systems and their respective load duration curves.

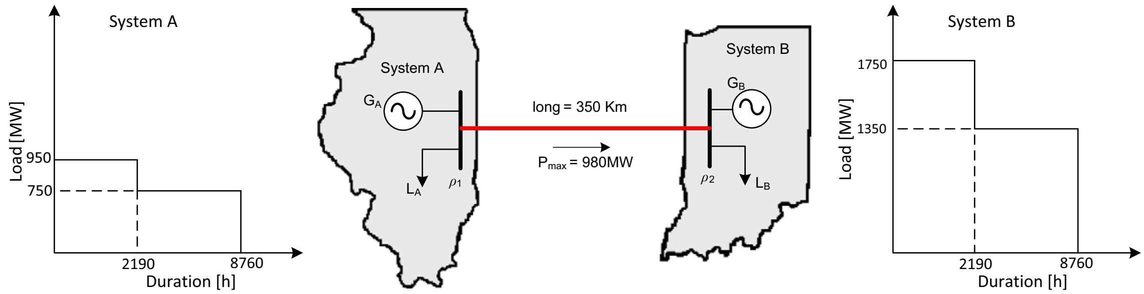

Fig. 2. Electric diagram of the example case and load duration curve.

In order to emulate conditions of the most advanced markets, it is considered that investments are made in a fully liberalized environment and the transmission project will be remunerated under a merchant approach. The independent system operator (ISO) allocates long-term financial transmission rights to the expansion holder according to the revenue adequacy criteria. Finally, under this market scheme, the regulator has minimal functions and mainly ensures system reliability. Under the merchant mechanism, the owner of the interconnector is entitled to collect the difference of locational marginal prices (LMP) between both systems times the capacity of the allocated long-term transmission rights (LTFTR). Lifetime of the issued LTFTR is 25 years from commissioning of the transmission line.

The evaluation considers that the project may be deferred for a maximum of 5 years, after this date the building license of transmission line expires. If the investor chooses to defer the project, it postpones the initial outlay and relinquishes the revenue stream that the project would generate immediately after commissioning.

The risk-adjusted discount rate or capital cost used to calculate the classic NPV is chosen 12%/a. This value is commonly used to represent the cost of equity on merchant transmission investments or projects with similar risk profile (Cosman, 2008). The risk-free discount rate to determine the value of the option to defer is considered 5% and represents the return of risk-free investments. Treasury bonds of the United States of similar maturity are regarded as a risk-free investment.

Thermal generation systems in both electric areas are considered. The installed power generation capacity and the reliability of the generating units are represented by an equivalent for each system. Regardless of the clustering of power plants in this example, the number of system components modeled under the proposed methodology is unconstrained.

4.2. Modeling uncertainties in transmission investments

The stochastic dynamics of uncertain variables that affect decision making on transmission investments is modeled by random processes. Since the real option valuation is made under the risk-neutral approach, each stochastic process must be adjusted to the risk-neutral world by applying the corresponding certainty equivalent (Trigeorgis, 1996).

The investment project decision is subject mainly to uncertainty in electricity demand growth, generation costs and availability of components. Another important source of uncertainty affecting decision making on transmission system investment is investment decisions of other market players such as electric generators. For the sake of simplicity in the exposition, this work assumes the transmission planner or the investor anticipates potential power generation investments in response to transmission system expansion, and consequently the generation facilities are considered known.

Under perfect competition, the assumption of known future generation is based on practical alternative proposed by Stoft (2006) called Practical Planning Policy. This specifies that the planner should optimize the transmission system taking actual and anticipated generation. For linear transmission investment cost, congestion rents are in the exact amount to recover optimal transmission capacity. This capacity produces efficient prices induce both, optimal investments in generation and transmission. As the optimal combined system can be perfectly anticipated, the current and future generation system is regarded as known without uncertainty.

However, under oligopolistic competition strategic and anticipative behavior of market participants may cause important deviations from the competitive results. For reproducing such market interactions under an oligopolistic market setting, game-theoretic equilibrium would need to be computed, which clearly is beyond the purpose and scope of this article. Accordingly, the proposed option valuation methodology does not preclude or restrict the consideration of uncertainties on investments in the generation facilities.

4.2.1. Electricity demand

The demand in each area is considered price-inelastic and is represented by load duration curves. The uncertainty in power demand is modeled as a Geometric Brownian Motion (GBM). The demand forecast can be adjusted by a GBM process, when it is assumed that the past trend is maintained over time. This hypothesis has been verified by Marathe and Ryan (2005). The stochastic process that follows the variable satisfies the stochastic differential equation:

$$dD_t = \alpha D_t dt + \sigma D_t dW_t \tag{10}$$

where D_t is the electricity demand at time t, α is the demand growth rate (*drift*), σ is the volatility or standard deviation of the growth rate, α and σ are considered constant over time. Finally W_t is a Wiener process with mean zero and variance one.

Under risk-neutral valuation, the term α is replaced by the certainty equivalent α^*. The certainty equivalent is numerically determined so that the present value of future cash flows generated by the investment project in the real world and the risk-neutral world is equivalent.

Fig. 2 shows the load duration curve to each of power system and Table 2 reports the parameters for the stochastic model.

4.2.2. Generation cost

The generation system is considered purely thermal, thus generating costs are directly related to fuel costs through the heat rate. Then, in order to determine the future behavior of the generation costs $C_i(P_{Gi})$ it is necessary to know the heat rate curve of generation units $H_i(P_{Gi})$ and the stochastic behavior of future fuel prices, K_i, being P_{Gi} the electrical power generated:

$$C_i(P_{Gi}) = K_i \cdot P_{Gi} \cdot H_i(P_{Gi}) = K_i \cdot P_{Gi}\left({}^{a\prime_i}/_{P_{Gi}} + b\prime_i + c\prime_i \cdot P_{Gi}\right). \tag{11}$$

Table 2
Stochastic parameters of electricity demand.

System	Growth rate [%]	Deviation [%]	Correlation factor
A	2.00	2.00	0.65
B	3.00	2.50	0.65

The fuel price dynamics is modeled as a Brownian motion with mean reversion, since the fuel spot price usually tends to revert to the long-run average price (Schwartz, 1997). In addition, the model adds a Poisson jump process to incorporate sudden price changes because of unusual events, e.g. economic crises and wars (Martzoukos and Trigeorgis, 2002). The stochastic process is therefore represented by the following stochastic differential equation:

$$dx = k(\bar{x}-x)\,dt + \sigma\, dW_t + q\, dP_t \tag{12}$$

where $\bar{x}$ is the long-term equilibrium price level and k measures the rate of mean reversion, σ characterizes the volatility of the process and dW_t is the increase of standard Brownian motion. Finally dP_t represents the Poisson jump process with an expected rate of event arrival λ_C and q the magnitude of the jump.

In order to simulate the stochastic process in the risk-neutral world, the drift of the process must be adjusted as follows:

$$k(\bar{x}-x) = k\left[\left(\bar{x}-\frac{\mu-r}{k}\right)-x\right] \tag{13}$$

where r is the risk-free rate, μ is the risk-adjusted return required for the type of fuel. Table 3 summarizes the parameters to simulate the stochastic behavior of the generation costs.

4.2.3. Availability of system components

The uncertainty in the availability of system components is modeled by a two-state Markov process. This model considers that a system component may reside in two mutually exclusive states, i.e. operation or failure. Fig. 3 shows the state diagram and possible transitions between them.

A simulation algorithm uses a non-chronological method to sample the states of all components, which in turn determine the system state. The sampling procedure is conducted assuming that the residence time in each state is exponentially distributed (Billinton and Allan, 1996). The failure and repair rates of system components for the example case are summarized in Table 4. Failure probability Pr(F) of each system component can be computed in terms of its failure and repair rates, λ and μ respectively, as follows:

$$\Pr(F) = \frac{\lambda}{\lambda+\mu}. \tag{14}$$

4.3. Revenue of the transmission expansion investment

Under the merchant expansion approach, the revenues generated by the transmission project are a function of the amount of long term financial transmission rights (LTFTR) allocated to network expansion and the difference of locational prices between the electrical nodes of the transmission branch. Since the investment project is a radial line, the LTFTR allocation is equivalent to the rated capacity of the new transmission line.

The expected annual revenue of the investment, $\mathbb{E}[R_m]$, is computed on each possible operation state the system can reside in. The state

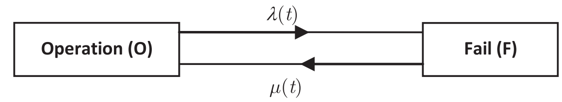

Fig. 3. Two-state renewable process.

space, E, is given by system load and availability of system components:

$$\mathbb{E}[R_m] = \frac{1}{E}\sum_{e=1}^{E}\left(\rho_j^e-\rho_i^e\right)Q_{ij}^e \cdot t^e \tag{15}$$

where: ρ_i^e and ρ_j^e are the locational marginal prices for the e-state in the bus i and j respectively, Q_{ij} is the capacity in MW of allocated LTFTR between the nodes ij, and t^e is the expected duration time of the scenario e in a year, [h/year].

4.4. The NPV classic valuation method

The classical investment evaluation consists of calculating the net present value of the project without flexibility ($\text{NPV}_{\text{classic}}$). The $\text{NPV}_{\text{classic}}$ is calculated as the difference between the expected present value of project revenues, $\mathbb{E}[VP]$, and investment costs associated with the project, C_{Inv}.

$$\text{NPV}_{\text{classic}} = \mathbb{E}[VP]-C_{\text{Inv}}. \tag{16}$$

The expected present value of revenues is estimated from Monte Carlo simulations. A large number of realizations of market variables along the lifetime of investment project are carried out. Then, samples of the annual cash flows of the project are obtained from computing optimal power flows (OPF) for samples of the system states. The OPF allows deriving nodal prices as the dual variables of the nodal equality constraints. The present values of the sample cash flows for each realization are calculated. Finally, the expected present value of project revenues is estimated by averaging the sampled ensemble.

For the exemplary case analyzed, the present value of revenues is 59.4 M$, which yields a classic NPV:

$$\text{NPV}_{\text{classic}} = 59.4-89.36 = -29.90[\text{M}].$$

As noted, the value of $\text{NPV}_{\text{classic}}$ is negative. Under the NPV technique criteria, the investment project does not create value for the investor, so the optimal decision rule would be to reject the project from further consideration. Consequently, if the investor considers only the traditional evaluation technique for assessing the investment projects, the interconnection line will not be built. Fig. 4 shows the probability distribution of $\text{NPV}_{\text{classic}}$, where there is a high probability, 71.5%, of obtaining a negative result.

4.5. Valuation of the option to defer

It is considered that the investment project has the option to be deferred for a period up to 5 years. The option to defer is a simple American option, i.e. the holder can exercise the right at any time before the maturity date, T, while uncertainties in the electricity market variables may be resolved, at least partially.

Table 3
Generating cost parameters.

Generator	Initial price [$/MBTU]	Long term price [$/MBTU]	Volatility	Reversion coeff.	Input–output function		
					a' [MBTU/h]	b' [MBTU/MWh]	c' [MBTU/MW^{2}h]
G_A	1.70	1.465	0.12	0.30	438.43	8.191	0.0064452
G_B	2.05	1.750	0.12	0.30	285.40	8	0.0073381

Table 4
Reliability parameters of system components.

Component	λ [h^{-1}]	μ [h^{-1}]	Failure probability
Generator A	0.000001	0.495	0.00000202
Generator B	0.000001	0.190	0.00000111
Line	0.005	0.0495	0.0917

The revenue function of the option to defer is:

$$F_i = \max\left[\left(PV_{M,i} - C_{M\ Inv,i}\right) - \left(PV_{F,i} - C_{F\ Inv,i}\right), 0\right] \tag{17}$$

$$PV_{M,i} = \sum_{t=i+1}^{i+H} \frac{\text{Revenues}_t}{(1+r)^{t-i}} \tag{18}$$

$$PV_{F,i} = \sum_{t=1}^{i} \text{Revenues}_t (1+r)^{i-t} + \sum_{t=i+1}^{H} \frac{\text{Revenues}_t}{(1+r)^{t-i}} \tag{19}$$

$$C_{M\ Inv,i} = C_{\text{Inv}_0}(1+q)^i \tag{20}$$

$$C_{F\ Inv,i} = C_{\text{Inv}_0}(1+r)^i \tag{21}$$

where $PV_{M,n}$ is the present value of revenues generated by the project if it is executed at year i, $PV_{F,i}$ is the present value of revenues, in the year i, generated by the project if the investment is executed without delay. C_{Inv0} is the initial investment cost; q is the growth rate of investment cost, H is the recovery period of investment and r the risk-free discount rate.

At maturity date, $i = T$, the value of the option to defer can be expressed as:

$$F_T = \max\left[\left(\sum_{t=T+1}^{T+H} \frac{\text{Revenues}_t}{(1+r)^{t-T}} - C_{\text{Inv}_0}(1+q)^T\right) - \left(\sum_{t=1}^{T} \text{Revenues}_t (1+r)^{T-t} + \sum_{t=T+1}^{H} \frac{\text{Revenues}_t}{(1+r)^{t-T}} - C_{\text{Inv}_0}(1+r)^T\right), 0\right]. \tag{22}$$

For a date earlier to maturity, the value of the option is:

$$F_i = \max\left[\left(\sum_{t=i+1}^{i+H} \frac{\text{Revenues}_t}{(1+r)^{t-i}} - C_{\text{Inv}_0}(1+q)^i\right) - \left(\sum_{t=1}^{i} \text{Revenues}_t (1+r)^{i-t} + \sum_{t=i+1}^{H} \frac{\text{Revenues}_t}{(1+r)^{t-i}} - C_{\text{Inv}_0}(1+r)^i, \Phi_{M,i+1}\right)\right]. \tag{23}$$

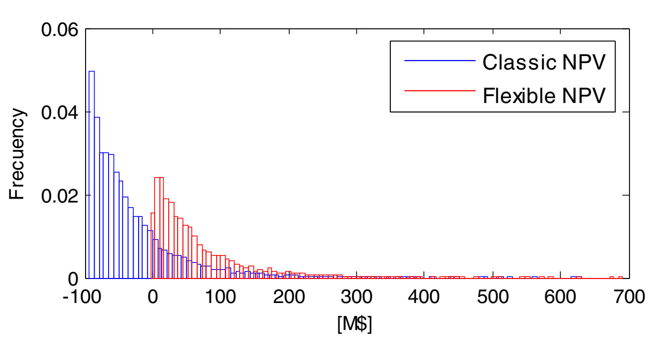

Fig. 4. NPV distribution with and without flexibility.

where $\Phi_{M,i+1}$ is the value of keeping alive the option until the time instant $i + 1$ and is estimated by least-squares regression.

Reordering the Eq. (23), the value of the deferral option can be defined as the difference of what is expected to earn less the revenue forgone to defer the investment.

$$F_n = \max[\text{Expected to earn} - \text{Revenue foregone}, 0] \tag{24}$$

$$F_i = \max\left[\left(\sum_{t=i+1}^{i+H} \frac{\text{Revenues}_t}{(1+r)^{t-i}} - \sum_{t=i+1}^{H} \frac{\text{Revenues}_t}{(1+r)^{t-i}} - C_{\text{Inv}_0}(1+q)^i\right) - \left(\sum_{t=1}^{i} \text{Revenues}_t (1+r)^{i-t} - C_{\text{Inv}_0}(1+r)^i\right), 0\right] \tag{25}$$

$$F_i = \max\left[\left(\sum_{t=H}^{i+H} \frac{\text{Revenues}_t}{(1+r)^{t-i}} - C_{\text{Inv}_0}(1+q)^i\right) - \left(\sum_{t=1}^{i} \text{Revenues}_t (1+r)^{i-t} - C_{\text{Inv}_0}(1+r)^i\right), 0\right]. \tag{26}$$

The value of the option to defer is obtained from the LSMC model described in the previous section. This method determines the value of the option at the initial time of the evaluation. In addition, the expected optimal time at which investment would be implemented in the future is determined.

Applying the LSMC approach, the value of the option to defer is 62.49 M$. The value of the option to defer is positive which allows increasing the project value when this flexibility is accounted for.

The value of the option to defer results from the new information that may arrive in next years. The option to defer allows waiting to decide to proceed with the project only if uncertainties are resolved favorably. If future conditions turn unfavorable, the investor will let expire the option and the transmission project is not carried out.

From the analysis of the optimal exercise time for 10,000 simulated paths it was observed that in 98.4% of the cases the optimal exercise path is waiting to the fifth year to execute the investment and 1.6% of the time the decision is waiting to the expiration of the option without exercising, i.e. the investment project is not executed.

The robustness of the assessment LSMC model is determined by calculating the value of the option to defer for great number simulated pathways of the driving variables. It is observed that the solution is very robust for a number of simulations greater than 1500. Fig. 5 illustrates the statistical convergence of value of the option to defer depending on the number of Monte Carlo realizations.

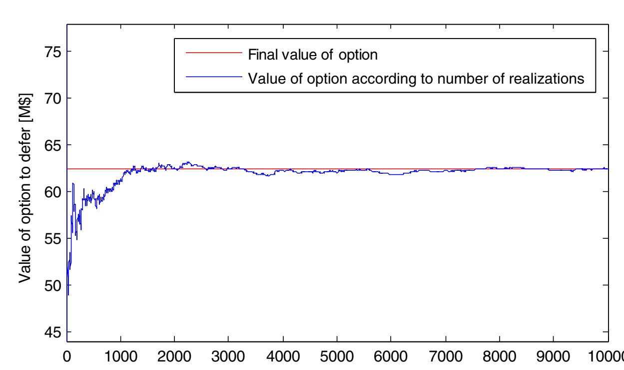

Fig. 5. Project value with flexibility according to the number of Monte Carlo generations.

4.6. Flexible NPV value

In order to determine the value of the project with flexibility to defer waiting for better information, Eq. (1) is applied:

$$NPV_{flexible} = NPV_{classic} + \text{Option value}$$

$$NPV_{flexible} = -29.90 + 62.49 = 32.59\ [M].$$

The total project value considering the option to defer is 32.59 M$. The value of the flexible project is greater than zero so the signal received by the investor is to keep the investment option open (without rejecting the project) and wait for market conditions turn favorable to reconsider whether carry out the investment.

Under the traditional assessment approach, i.e. the classic NPV, the investment project had been rejected definitively. When the flexibility to defer the investment has been considered, the value of the project is positive and therefore represents an attractive investment opportunity regardless the current decision is delay construction until the next assessment period. Consequently, flexibility to delay decisions allows irreversible investment projects, as is the case of transmission investments, not to be dismissed immediately as they may represent attractive opportunities for investors. Fig. 4 shows the probability distribution of the NPV considering the project with and without flexibility.

4.7. Analysis of parameters influencing the value of deferral options

The value of the embedded real options in an investment project is affected by various market parameters. These parameters are mainly the underlying asset value, the exercise price of the option, the volatility of uncertain variables, and the expiration date of the option.

The value of underlying asset of an investment project is the present value of cash flows generated by the project; meanwhile the present value depends on the value of the discount rate or risk-adjusted capital cost. If the capital cost is increased, the value of underlying asset decreases and vice versa. The option to defer, equivalent to a financial call option, decreases its value with the decrease of the underlying asset value or, in our case, with the increased cost of capital.

If the value of the option to defer is low, the investor will avoid postponing the transmission line and the project will be executed as soon as possible, provided that the flexible NPV is positive.

The influence of the risk-adjusted capital cost for financing transmission projects upon the deferral option value can be assessed by applying ROA. The behavior of flexible NPV for the investment project in function of the discount rate is shown in Fig. 6.

In case of a discount rate higher than 14%, even though the option to defer for 5 years has a positive value, the $NPV_{flexible}$ of the project has a negative value. Hence, the project would not be implemented even at

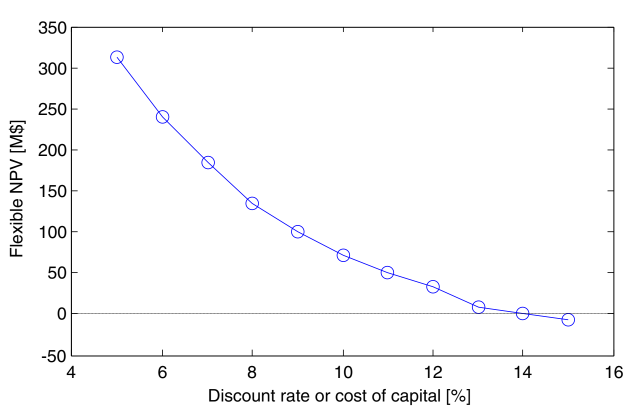

Fig. 6. $NPV_{flexible}$ for different costs of capital rate.

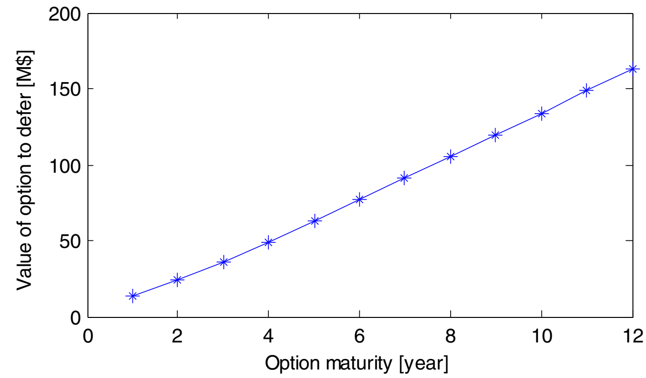

Fig. 7. Option value according to maturity date.

the expiration date. In this case, it would be necessary to analyze the value of the $NPV_{flexible}$ for option maturities higher than 5 years.

In order to understand the value of the option with increasing maturity time, a sensitivity analysis with a cost of capital of 12% is performed. The results from this analysis show that as the expiration date extends the value of the option increases, as shown in Fig. 7. This behavior is explained by the fact that investors has more time to wait for valuable information and for resolution of key uncertainties in order to make better decisions.

If the option to defer the transmission project does not expire, i.e. the building license has an indeterminate maturity, the economic signal for investors would be to defer construction perpetually because the value of the option is growing every year.

Furthermore, the ROA can also help regulators and planners to analyze the behavior of transmission agents and define optimal policies to encourage investment in the transmission system, in this case by changing expiration time of building permits (Pringles et al., 2014).

Furthermore, the value of the deferral option is analyzed when the prevailing uncertainty in power demand is higher, i.e. the volatility of the consumption growth rate is increased. The demand uncertainty levels are shown in Table 5.

It is noted that higher uncertainty in demand growth increases the value of the option to defer. This is because there is a higher probability of increasing profits by keeping open the option to defer while the risk of losses is limited. Fig. 8(a) illustrates the value of the option to defer for a capital cost of 12% and maturity of 5 years. The option value according to uncertainty in demand growth and according to maturity date of the option is depicted in Fig. 8(b). It is observed that the greater the uncertainty in demand growth the higher the option value.

Finally, the behavior of the option to defer with respect to annual escalation of the investment cost is analyzed in Fig. 9. It is observed that option value decreases for increasing value of the annual growth rate of the investment cost. This replicates the behavior of financial call options, whose value decreases as the strike price increases.

Consequently, the economic signal observed by the investor is executed as soon as possible the transmission project, since the option to defer loses value. This shows that in a context of sustained escalation of the investment costs, the time to defer the transmission line is shortened, appearing almost immediately the transmission expansion.

Table 5
Volatility of growth rate of demand.

Level	System	
	A	B
1	1.50%	2.00%
2	2.00%	2.50%
3	2.50%	3.00%
4	3.00%	3.50%

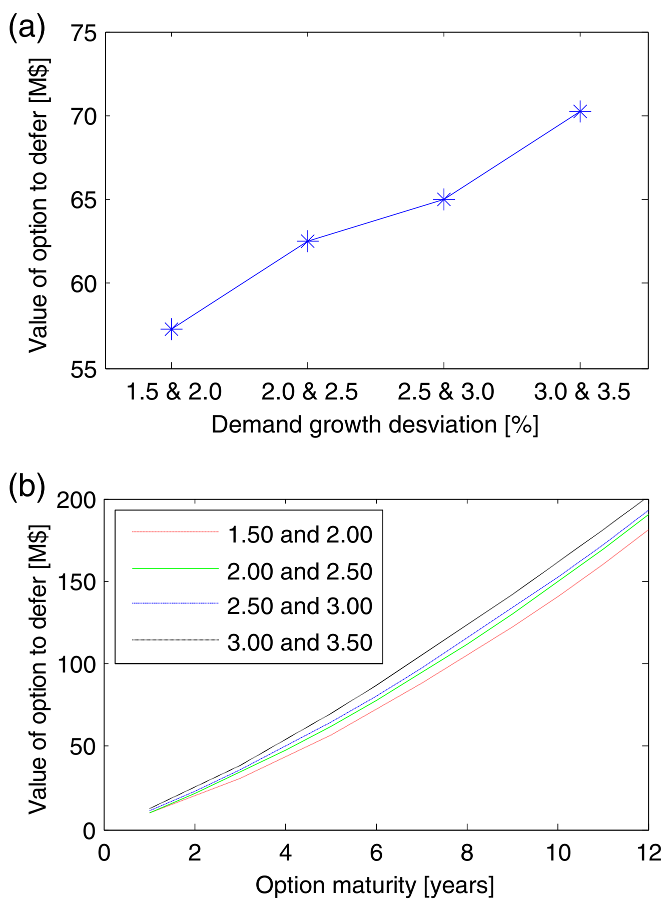

Fig. 8. Value of the option to defer according to load growth volatility.

4.8. Decision regions by real option analysis

Once determined the value provided by flexibility, in this case the flexibility to defer commitment, and the flexible NPV value of the project, different areas of decision can be graphically represented. These areas are function of the parameters that influences the value of the project. In this example, the decision regions (invest, defer, reject) depending on the initial investment cost and opportunity cost of capital are defined. Table 1 sets out the rules for determining each of the decision regions.

In order to define the decision regions, the option values, classic NPV and flexible NPV of the investment project for the different values of the input variables must be computed. First, the value of opportunity cost of capital (input 1) and the initial investment cost (input 2) is varied. In this way, a bivariate sensitivity analysis of decisions can be carried out. From the results obtained and the conditions specified in Table 1, the values of the inputs that define the borders among different possible decisions are determined.

The decision-making according to the opportunity cost of capital and the initial investment cost is shown in Fig. 10(a). In this case, it is considered that the initial cost has an annual increase of 15%. Two regions are clearly observed, the decision to defer the investment and the decision to reject the investment regardless the value of the deferral option. Even though the option value is always positive, for some parameter is not enough and the flexible NPV is negative.

Fig. 10(b) illustrates the decision regions but with an annual increase of the investment cost of 90%, although it is a very high value, it has been considered to be able to highlight all regions at time of decision making.

In this case, there is a region in which the option to defer has no value because the increase in costs is greater than the increase in returns of the transmission project. Even so the project is profitable, so in this case the investment is carried out immediately. In addition, there are areas where the project could be delayed or rejected depending on the cost of capital and the cost of the initial investment considered.

5. Conclusions

This paper proposes real option analysis as a modern appraisal tool for properly assessing the value of strategic flexibility embedded in power transmission investments. This valuation approach allows incorporating managerial flexibility for dealing with the different sources of uncertainty prevailing in the current liberalized electricity markets.

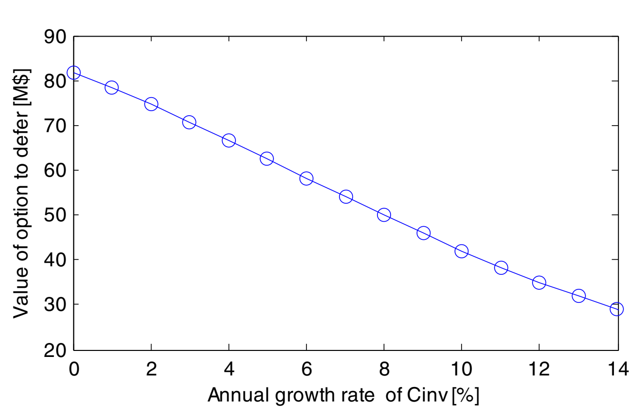

Fig. 9. Value of the option to defer according to initial investment cost.

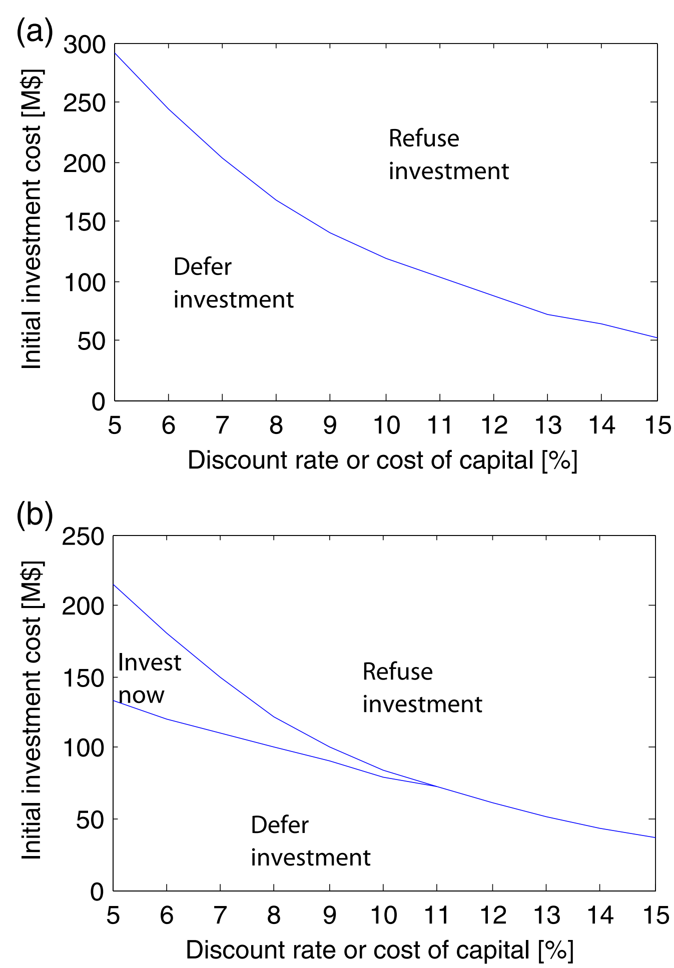

Fig. 10. Decision regions according to the initial investment cost and the discount rate.

The use of this valuation approach has an important impact on decision-making in transmission investments. In fact, by applying real option analysis, the risks of losses are mitigated because the project is not executed if an unfavorable scenario arrives at the moment of exercise the option and profit opportunities are maximized because the project is executed only if a favorable scenario develops.

To determine the value of the real options, a simulative procedure named Least Squares Monte Carlo is proposed as evaluation methodology. The LSMC approach is based on Monte Carlo simulations and recursive stochastic dynamic programming. The proposed method allows pricing American-type options, accounting for several sources of uncertainties and different types of stochastic dynamics, which constitute distinctive characteristics of the options embedded in transmission investment projects.

The uncertainty on market variables has a significant impact on investment decisions in power transmission infrastructure. Real option analysis considers attractive investments that would be immediately rejected by conventional valuation tools. Thereby, the application of ROA encourages more efficient investments in transmission systems.

In the investigated example case, the interconnection project of two power systems was not profitable under the traditional evaluation approach. However, the project becomes economically attractive when the option to defer the investment decision is considered. In this case, the optimal decision is to get involved in the business by acquiring a building license and waiting for the resolution of key uncertainties. If at expiration date of the license the project is still unprofitable, the line is not built and the investor only losses the cost incurred to acquire the construction permit at early time.

Sensitivity analysis illustrates the impact of different factors on the monetary value of the postponement option. The value of the option to defer increases as the level of uncertainty is higher. The increase of the option value reflects the worth of waiting to see how variables develop in future without prematurely rejecting the investment project.

Additionally, the impact of the underlying asset value on the value of the option to defer was assessed in this study. The valuation shows that a reduction in the present value of revenues due to escalation in capital costs decreases the value of the deferral option. It is also shown that an extension of the expiration date increases the value of the option to delay decisions. Consequently, in irreversible transmission investments that have the option to defer and are not economically profitable, by extending the maturity date of construction permits the value of transmission projects is increased. This flexibility can turn a project into economically attractive if business conditions become favorable.

The impact of growth of investment costs on the value of the option to defer the transmission investment has been analyzed. For the study case, decision regions as a function of the initial investment costs and the opportunity cost of capital have been determined. Decision regions enable mapping decisions to decide whether execute, postpone or reject the transmission interconnection proposed.

Finally, under oligopolistic market setting is important to consider the strategic uncertainty between generation and transmission system. This interaction is beyond the purpose and scope of this article. However, the proposed option valuation methodology does not preclude or restrict the consideration of this analysis. The strategic interaction between transmission and generation investments in the context of investment appraisal is an important issue that will be addressed in future papers.

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