ECONOMICALLY ADAPTED TRANSMISSION SYSTEMS
IN OPEN ACCESS SCHEMES
-APPLICATION OF GENETIC ALGORITHMS

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Abstract- A dynamic transmission planning methodology using a genetic algorithm is formulated for the purpose of determining an economically adapted electric transmission system in a deregulated open access environment. Transmission investment sensitivity information linked to short term marginal income is used. A computer program is developed and applied to obtain a long range adapted transmission grid for the Chilean electrical system. Two open access pricing methodologies are evaluated in a spot price framework, as applied to the adapted grid over the time horizon.

Keywords: transmission open access, transmission planning, transmission expansion, genetic algorithms, transmission cost allocation, spot pricing, marginal cost, transmission regulation.

I INTRODUCTION

Transmission open access is receiving increasing attention by power utilities and regulatory state bodies worldwide [1,2]. Many countries have considered or are considering deregulating their electric power sectors to allow for competition among generators and to create market conditions in the sector, that are seen as necessary conditions for increasing the efficiency of electric energy production and distribution, offering a lower price, higher quality and more secure product. A necessary condition for competition to take place is that of generators being able to reach consumers through the transmission network, which can be achieved through open access schemes.

Different approaches have been followed to create open access conditions in interconnected power systems. Issues such as transmission costing and pricing, payment allocation, access policies, transmission rights, are been extensively discussed and there are not yet clear cut answers that can be applied universally. One of the issues that poses difficult questions is that of the transmission system expansion.

II ECONOMICALLY ADAPTED TRANSMISSION SYSTEMS

A. Planning in a deregulated environment

In the traditional vertically integrated regulated electric utility, generating and transmission expansion plans are coordinated, so that the network does not restrict optimal dispatch, the network itself is not overloaded and specific desirable technical conditions are achieved (adequate voltage profiles, damped system dynamics, etc.) The environment in an increasing competitive deregulated electrical sector, where generators look for their own individual economic interests, while sharing an open access network, is very different. The development of transmission is seen differently by each of the participants, and while a particular capacity expansion may be of interest to one party, there will be others that may be against it (whether because it will affect their operation and/or income or whether they may be asked to contribute to an investment they may not see as beneficial). Transmission planning in a competitive economic environment is clearly an emerging complex issue [3].
The Chilean and Peruvian electric regulations have faced this issue through the coining of a novel concept: the "economically adapted" transmission system. The Chilean 1982 electricity law [4] provides a general definition: "an installation is economically adapted when it allows to produce a given quantity at the lowest cost". Penalty factors, based on an adapted transmission system, are calculated by the regulator and are used to spatially distribute spot prices to main buses. The Peruvian 1992 legislation [5] delimitates the definition by indicating that "an economically adapted system is that electrical system where there is an equilibrium between energy offer and demand, seeking for reduced costs and maintaining quality of service". The Peruvian regulator not only is responsible for determining the adapted transmission system, but restricts the transmission owner income based on that adapted system. The objective is to stimulate efficient investment, maintenance and operation.

B. Economic adaptation

The economic adaptation notion relates to concepts formulated by Boiteux in 1949 [6], based on the economic principle that the social optimum is achieved when in an economy, the goods and services are priced at marginal costs and systems are economically adapted. In such adapted systems, the returns obtained from the sale of all the energy at the instantaneous marginal cost, plus returns from the sale of all power at the development cost of the appropriate units to provide peak power, are equivalent to the cost of capital plus the total operation costs of the generating plants [7]. This is the case for systems with no economies of scale. It is formulated that the combination of the generation and transmission businesses does not have economies of scale, even with transmission itself having such economies. Therefore, it is concluded that marginal pricing provides enough revenues for the combined businesses.

Electrical engineers usually understand an adapted system solely as the one where electricity offer physically matches demand. However, the concept is really an economic one, where the social optimum is looked for, with costs minimized over an horizon of time; in theory, there may be a case where offer and demand do not match during a period of time, if the cost of not serving energy results in a lower global cost. The adaptation has to be evaluated over a period of time, rather than instantaneously. Boiteux formulated adaptation as a step wise condition, given the discrete character of investments. In an economically adapted system, short term marginal costs equal long term marginal costs. Boiteux indicates that "provided there is an optimal investment policy, short term pricing is also long-term pricing, and there is no longer any contradiction between the two".

The economic interpretation of an adapted transmission system requires therefore to optimize transmission development over time. Dynamic planning methodologies are required for the optimization.

III TRANSMISSION PLANNING

A. Planning methodologies

Transmission planning is a large scale problem that is complicated by the many factors it has to consider: technical and economic transmission characteristics, performance uncertainties, inter temporal and spatial dependences, link with generation planning, etc. Planners have usually simplified the problem by decoupling the transmission from the generation planning, the second one being done without consideration of the first, or with a gross representation of transmission investments. The logic behind this is that transmission investment is usually a minor part of the global business; besides, particular transmission lines may be associated with specific generation investments. Nevertheless, it is clear that this decoupling is a simplification and it has been used as a way to cope with the complexities of the global problem.

Transmission planners have worked mainly with static models that analyze one year in the planning horizon and evaluate required expansion alternatives. The static model is a sub problem of the general dynamic model, that few researchers have dealt with. The most common approach is to use static models in a dynamic context. Reference [8] contains a comprehensive transmission planning state of the art summary. Several classical optimization techniques have been used: linear programming [9], non linear programming [10], mixed integer programming [11,12], Benders decomposition [13,14], and others. Heuristic models have also been utilized, based on sensitivity analysis [13,15,16].

Computer developments in the area of parallel processing have originated much interest in optimization methodologies that can treat large scale problems in parallel in a computer cluster. Heuristic dynamic methodologies for transmission planning, using genetic algorithms, suitable for parallel implementation, are proposed and formulated in this work.

B. Planning in the Chilean and Peruvian regulations

The Chilean and Peruvian electric regulations leave the development of the generation and transmission systems to the market and private investors, but provide an indicative plan from a social point of view. The Chilean pricing systems, both free and regulated, have been sufficiently attractive so that the required generation investment has taken place without government intervention [17].

Both legislations indicate that the generation-transmission indicative plan must be evaluated by the regulator every six months. In practice, the regulators have only provided indicative plans for generation investments, with only major transmission lines included, for the same reasons that planners worldwide have decoupled both planning problems. Nevertheless, the challenge in both regulations, for pricing purposes, is to determine the adapted transmission systems, given the existence of a previously determined indicative plan.
for generation. Transmission is understood as the high voltage meshed network that is shared by all. Radial transmission or subtransmission used by individual generators or consumers is left out. Within the described framework, the economically adapted transmission system is the one that provides the transmission service at minimum cost. However, minimum cost does not only refer to the cost of transmission investment and losses, but should also include variable cost of generation. Therefore, in the resultant optimization problem, the objective function, evaluated over a time horizon \( T \), is

\[
\text{Min} \ F = \sum_{i=1}^{T} \left[ C_{\text{trans}}^i + \sum_{j=1}^{N} (C_{\text{gen}}^j + C_{\text{near}}^j) \right]
\]

where

- \( i = 1, \ldots, T \) number of time periods
- \( i = 1, \ldots, N \) number of buses
- \( C_{\text{trans}}^i \) transmission and transformation investment annuities
- \( C_{\text{gen}}^j \) annual variable cost of generation
- \( C_{\text{near}}^j \) annual cost of non served energy

subject to

- an optimal generation investment indicative plan
- generation operational costs
- estimated load growth and distribution
- predefined transmission paths or rights of way

Optimization is achieved by controlling transmission investment decisions. This is done by selecting, for each transmission path, one of several discrete transmission investment alternatives and one of several time periods. The problem must then combine two stages of optimization, that feed information into each other, operation and investment. A methodology using genetic algorithms is proposed for solving the problem.

IV GENETIC ALGORITHMS IN TRANSMISSION PLANNING

A. Genetic algorithms

An emerging heuristic optimization methodology, the genetic algorithms (GAs), is proposed to solve the transmission planning problem. The main idea of the GAs originates from the mechanisms of Nature, that through natural selection and genetics determine that "the fittest member of a population has the highest probability for survival and reproduction". GAs combine an artificial survival of the fittest with genetic operators abstracted from Nature to form a surprisingly robust search mechanism [18]. Tools applying GA are said to find a global optimum for mathematical problems having a multiplicity of local optima and hard non convexities. Highly complex problems such as the traveling salesman problem, turbine design and pipeline scheduling have been solved successfully [19]. GAs have also proved powerful in optimization processes in different power system applications [20,21,22].

B. Genetic algorithm steps

The genetic optimization algorithm, as applied to transmission planning, observes the following steps [19,23]:

i) Binary codification: the different variables that characterize the solution to the problem and that condition the value of the objective function are codified in binary form. The genetic code obtained corresponds to a string of ones and zeroes, that represents in a unique form each member of the population (in this work, each member corresponds to a given transmission planning solution). Two sets of variables to build the code are chosen in this work (Fig. 1):

- transmission investment alternative for each defined path
- commissioning year for a given transmission investment

Fig. 1. Binary codification of transmission problem

Therefore, each combination of coded variables corresponds to a solution of the problem, which the GA will use to determine the optimal solution.

ii) Initial population: as in Nature, where there is a set of individuals that will evolve, the GA needs the definition of an initial population (as indicated, each member of the population in the case of this paper is a given transmission plan, coded in a string of 1s and 0s). The initial population is usually chosen in a random form by GA researchers, and part of the population used in this work was selected randomly (random formation of initial transmission expansion plans, following a feasibility logic). This work adds expert criteria to create new members of the initial population, based on engineering logic that uses electric sensitivities (Appendix A). These new members improve significantly the convergence of the GA.

iii) Fitness: the fitness of each member of the initial population (i.e., each bit string) is determined through a fitness function (in an optimization problem, it is the objective function). In the transmission planning problem, as indicated before, the fitness function is the sum of transmission and transformation investments, plus the expected operational costs (unserved energy included). It does not correspond to an analytical function, but, rather, the resultant value obtained through a simulation of a given transmission plan, as described in Appendix B.

iv) Ranking: the fitness function allows the ranking of the members of the initial population; the set of transmission expansion plans is ranked, the fittest members given more chances to survive for the next generation.
v) **Crossover:** this step initiates the selection process using the genetic information previously prepared. The initial population (initial transmission plans), already ranked, is used for a crossover process. A portion of the genetic code of one high rank member is exchanged with that of another member, giving birth to two children (two new expansion plans). The new members maintain many of the essential characteristics of their parents. The objective is to combine different high quality transmission plans in the search for an optimum one.

vi) **Mutation:** as in Nature, mutation is considered to add genetic diversity to the existing population (with the advantage that new radical alternatives may be considered). Part of the genetic code of some members are randomly altered. That means that some expansion plans are changed, e.g., new lines are added or commissioning times are shifted. This step, different to the crossover one, is able to generate genetic codes that can not be built from a combination of existing member codes.

vii) **New generation:** the original population grows through the addition of new members resultant from the crossover and mutation steps. This enlarged population is ranked with the fitness function. A reduction of that enlarged population is made, using the ranking, in order to maintain the original population size. Therefore, a new generation is then determined, as a mixture of some members of the previous population plus some new members resultant from the crossover and mutation steps. Poor transmission plans have been eliminated.

![Diagram of transmission planning genetic algorithm](image)

**Fig. 2.** Transmission planning genetic algorithm

The above steps are integrated into an iterative process, with new populations replacing previous ones, until a convergence criteria is reached. The algorithm for the optimal transmission plan using the above concepts is illustrated in

**Fig. 2.** Convergence is achieved when all the members of the final population have identical genetic codes; otherwise, the iterative process is stopped when the objective function is not improved after a given number of iterations or when a maximum number of iterations is reached.

### V APPLICATION STUDIES

A computer code using the GA previously described was integrated in Hewlett Packard 715 workstations, using C and Fortran 77. The tool incorporates a database and an operation linearized dispatch algorithm [24], a public domain GA module modified by the authors, and a user interface module. Multiple test cases were run to evaluate the potential and effectiveness of the tool. In all cases, transmission plans provided by experienced users were considerably improved by the algorithm.

#### A. Economically adapted Chilean transmission system

The determination of the economically adapted transmission system for the main Chilean power grid was made using the developed tool. The system is characterized by its radial longitudinal structure (2000 km), with most of its generation installed capacity being hydro (75%) and located in the south of the network. Load is concentrated in the central region (70% of total load). Reservoirs with important storage capabilities are in the south, while the most efficient thermal generation is next to the load.

The economic adaptation is searched in a ten year horizon, considering yearly stages. Initial maximum demand is 2530 MW, with a 6% load growth rate and a 0.67 load factor. A discount rate of 10% is used, considering a useful life of 30 years for transmission equipment.

![Diagram of Chilean electrical system-reduced model](image)

**Fig. 3.** Chilean electrical system-reduced model

To illustrate results, the paper reports the application of the tool to a reduced model, that keeps the main generation, transmission and load features of the original Chilean system. The reduced system models 8 buses and 10 possible line paths (Fig. 3). The network considers lines installed in all paths, except for paths West1-East and North2-West2, that are
available starting on years 4 and 8 respectively. Within the horizon, the model considers 6 thermal plants, 5 run of river hydraulic plants and one large reservoir plant. Four alternative investment schemes were considered for each path. The alternative schemes may combine three voltage levels (154, 220 and 500 kV) and single and double circuits.

Table 1, that summarizes the results for the best five plans after 10 iterations. Aprox. 2500 plans are simulated, each simulation covering 90 economic dispatches, corresponding to 10 years, 3 load levels and 3 hydrological availability conditions. CPU requirements are 8 hrs. in one HP workstation.

<table>
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<th>Costs (kUS$)</th>
<th>Base</th>
<th>Plan 1</th>
<th>Plan 2</th>
<th>Plan 3</th>
<th>Plan 4</th>
<th>Plan 5</th>
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<td>524937</td>
<td>519097</td>
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<td>520922</td>
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<td>Investment:</td>
<td></td>
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<tr>
<td>Transformers</td>
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<td>40111</td>
<td>39864</td>
<td>39990</td>
<td>37210</td>
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<td>96820</td>
<td>977070</td>
<td>983884</td>
<td>989125</td>
</tr>
</tbody>
</table>

Fig. 4. Initial transmission expansion plan

An initial expansion plan is proposed (Base Case), as shown in Fig. 4, with changes in transmission installations in years 4, 7 and 8. This initial plan corresponds to one member of the initial population. The genetic code for each path, with the variables previously defined, is given by 16 bits in packets of 4. Four alternative investment schemes were considered and four bits were used to identify the investment commissioning period (discrete timing of investment). For example, for path South1-South2 with a double circuit 500 kV line in year 1 and an addition of a double circuit 220 kV line in year 7, the coded string for the initial plan is:

```
0000 0111 0000 0001
```

New members of the population were created from that proposed plan, incorporating changes randomly generated as well as changes determined from electric sensitivities. A total population of 400 plans was used and the genetic algorithm was successful in improving the proposed plan, as shown in

Fig. 5. Adapted transmission network expansion plan
The best plan obtained, as compared to the base case, reduces in 85 million dollars the present value of the total cost, reducing both total investment and operation costs.

VI ALTERNATIVE TRANSMISSION PRICING METHODOLOGIES

The impact of two pricing methodologies on the determined adapted transmission system was evaluated. Two supplement wheeling allocation alternatives [24] were considered:

i. Generalized Generation Distribution Factors, based on the use of system, which represent the impact of total generation change in total flow over each system line.

ii. Proportional to installed capacity of each generator

Simulations of the system were made, considering optimal generation dispatches over the ten year period, with the generation plan and demand growth used when determining the adapted transmission system. Maximum load and a medium hydrological condition were considered. Wheeling payments were to be allocated to generation buses, irrespective of the presence of different plant owners in those buses. Figs. 6 and 7 illustrate the collected marginal revenue [24] and the resultant allocated payments along the horizon, when using the two indicated alternatives. The distribution of payments, based on use of system, changes considerably over the study horizon, providing a variable economic signal. The allocation based on generation capacity is more stable, although total capacity varies from 3155 MW to 5465 MW over the ten years. Nevertheless, the more essential question is which allocation provides a more sound investment signal, from a social point of view. The authors are studying the problem with the reported tools.

Even though the generation-transmission system has been optimized, line saturation conditions appear at different stages (the optimization finds it preferable to additional investment). This is the case for year 1, when the path South1-South2 is saturated, collecting a marginal revenue larger than its required annual revenue. The same happens for years 6 and 8 to 10.

VII CONCLUSIONS

The proposed planning methodology based on a genetic algorithm proved a useful tool for the determination of an economically adapted transmission system, as required for indicative expansion plans and transmission pricing in deregulated open access legislation. Alternative transmission pricing schemes can be assessed with the tool and questions of economic efficiency can be addressed.

The authors are now incorporating changes in the generation indicative plan with a heuristic approach, but are also exploring the application of the genetic algorithms to the combined generation-transmission planning. Parallel processing is also being studied.

The transmission open access issue is a very complex one, where technical and economic questions intermix in a convoluted dynamic manner. The paper contributes with a computer tool that can help address both questions together.

Fig. 6. Wheeling allocation based on use of system

Fig. 7. Wheeling allocation based on installed capacity

VIII ACKNOWLEDGMENT

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IX REFERENCES


series susceptance $\gamma_{lm}$ and transmission capacity (the network model is utilized in a dispatch algorithm based on DC load flows and incorporating losses). Therefore, an incremental change in those parameters (because of a new transmission investment) produces a change in the objective function $W$, given by [8,16]

$$
\Delta W = \Delta \gamma_{lm} (\pi_{pk} - \pi_{pw})(\theta_k - \theta_m) +
\Delta G_{lm} [1 - \cos(\theta_k - \theta_m)](\pi_{pk} + \pi_{pw})
$$

where

$\pi_{pk}$ dual variable associated to power balance at bus k

$\theta_m$ final value of voltage phase angle at bus k

Sensitivities may be evaluated for each transmission path. The assumption is made that there is a linear relation between the actual line parameters $\gamma_{lm}^*, G_{lm}^*$ and the investment variable $X_{lm}$. This allows to consider the lump discrete character of investments. Therefore, the objective function changes with an investment in line k-m as:

$$
\frac{\Delta W}{\Delta X_{lm}} = \Delta \gamma_{lm}^* (\pi_{pk}^* - \pi_{pw}^*)(\theta_k - \theta_m) +
\Delta G_{lm}^* [1 - \cos(\theta_k - \theta_m)](\pi_{pk}^* + \pi_{pw}^*)
$$

It must be emphasized that the sensitivities correspond exactly to the transmission marginal revenue in a spot priced transmission pricing scheme [24]. Actually, the larger the marginal revenue in one system connection, the more convenient it is to invest in that connection (it is a socially convenient, because, on the contrary, it is a perverse incentive for private investors). Large marginal revenues are usually associated to strong transmission saturation.

**APPENDIX B - SIMULATION**

As indicated, the economic evaluation of a transmission expansion plan involves both determining investment and operation costs. Operation costs are obtained through a simulation of the generation-transportation system over the time horizon, assuming an optimal dispatch strategy. The simulation considers a given generation investment plan, including thermal plants as well as run of river and reservoir hydro plants, each with maximum and minimum generations. Fuel costs for thermal plants are used, while the strategic value of stored water for each reservoir plant is incorporated, thus representing the necessary hydrothermal coordination (previously, a hydrothermal dispatch program determines the value of water [25]). The hydrologic stochasticity is modeled through the consideration of equiprobable dry, medium and wet years. Maximum demand, load growth, load factor and cost of unserved energy are specified for each bus. Demand is modeled through the duration curve, divided in three steps of different widths. The computer code was built to consider a maximum of 15 periods (each period can be one or more years).

**APPENDIX A - SENSITIVITIES**

The sensitivities, used for creating new expansion plans for the genetic algorithm, relate operational cost impacts with transmission investments. A line joining buses k and m is characterized by three parameters: series conductance $G_{km}$.
The optimal dispatches for each period (and each hydro year and each load level) provide operational costs and unserved energy costs (to obtain expected value of operation) as well as dual variable multipliers (to calculate sensitivities). Values are weighted in relation to their time duration.

Operation costs obtained and investment values are used to evaluate fitness in the genetic algorithm, allowing the ranking of each expansion plan. Security levels are imposed by considering pre defined contingencies that are used as an initial filter to eliminate unsecure expansion plans. Unserved energy costs also impose a certain security level in the optimization process.

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Discussion

Kit Po Wong (Artificial Intelligence and Power Systems Research Group, Department of Electrical and Electronic Engineering, University of Western Australia, Nedlands 6009, Western Australia): The authors are to be congratulated on an interesting paper on the application of genetic algorithms to transmission planning in a deregulated open access environment. The paper has contributed to the area of the establishment of new methods for transmission planning and has demonstrated the potential of the new planning methodology developed in the paper for practical use.

Genetic algorithms have recently been applied to a number of optimization problems in power system operations such as economic dispatch and unit commitment. These algorithms have been shown to be able to deal with the non-convexity of combinatorial optimization problems and have the ability to seek for the global optimal solution. Among other factors, the performance of the genetic algorithms depends on the representation and the coding method of the solutions in the chromosomes; the fitness function and the methods of crossover and mutation. With reference to these factors, comments and clarification to the following questions are requested:

1. What do the elements in the chromosome represent? Would an integer coding scheme be better than the pure binary coding method for the problem in the paper?

2. Should a yearly planning interval be adopted so that more planning alternatives can be investigated by the evolutionary process in the genetic algorithms?

3. What is the fitness function used? By itself, the objective function formulated in the paper cannot be employed directly as the fitness function, because the objective function represents the total cost to be minimized, but the process in genetic algorithms attempts to maximize the fitness values of the solutions.

4. What are the methods of crossover and mutation used?

5. The child chromosome generated by crossover or the mutated chromosome after mutation may contain an infeasible plan. What measures can be developed to ensure the new chromosomes contain feasible plans? Such measures will be useful to assist the genetic algorithm to find the optimal solution and to reduce the computing time.

6. In the application example, a population size of 400 has been used. What are the values of the total number of generations (iterations), probability of crossover and probability of mutation employed?

7. Have the authors experienced any convergence problem with the algorithm developed? What steps have the authors used to ensure that the solution plan obtained by the algorithm is the most appropriate plan?

8. What is the repeatability of the developed genetic-algorithm planning tool given that there is randomness in the nature of genetic algorithms?

Y.M. Park (Seoul National University, Seoul, Korea): The authors are to be complemented for the work presented in this paper. This work can be looked as follows:

i) A general dynamic transmission planning methodology in open access schemes,

ii) and, applying genetic algorithm to above mentioned problem.

The discussor would appreciate authors' comments on the following questions. Once again the discussor would like to appreciate the authors for their interesting work on application of GA to transmission expansion planning problem in electric power systems.

1) The author's paper did not present the comparison data between conventional methods and proposed GA for solving transmission planning. Would you present the comparison under the same situation in terms of computation time and results?

2) There are some control parameters in utilizing GA, such as population size, crossover and mutation rate. What are the values of parameters used in authors' paper? Are there any specific criteria to choose the parameters?

3) I think that the transmission planning is a very complex, nonlinear, and dynamic problem, therefore it may be difficult to apply conventional simple genetic algorithm to the problem directly. Accordingly, the authors probably used ranking selection method and expert criteria based on sensitivity in creating initial population. Would you refer to the effect to use above mentioned methods?

4) It is known that the representation and order of genetic code arrays have some effects on the results of GA. Do the genetic code arrays used in authors' paper have any special meaning?

X. Vieira Filho, Boris G. Gorenstin (Cepel, Brazil) and M. V. F. Pereira (PSRI, Brazil): The authors are to be congratulated for one more excellent contribution to the difficult task of planning power systems within a deregulated framework. The introduction of a genetic algorithm to determine the economically adapted transmission system is, in fact a very promising tool for optimizing the indicative generation/transmission plan. It starts with defined a best generation plan, and optimization is performed to find the economically adapted transmission system.

Some comments arise from the analysis of this interesting paper.

First, it seems clear that in an environment for competition in generation it is of paramount importance to produce periodically a "reference planning" in a centralized way. Although the authors mention that this reference plan is performed by regulators, there are doubts if a regulator should
also coordinate the technical economical planning activity.

A transmission planning where a fixed generation expansion is established may not correspond to the actual situation in deregulated frameworks. Actually, when there is free competition in generation, starting from a planning stage, private investors may wish to build new plants in any points of the system. Transmission planning then is still more complex, and require some different steps. One possible approach is the one proposed in reference [1], where a "reference plan" is established based on the economic signals provided by the transmission entity to private investors. For hydrothermal systems, there is a special concern for the generation expansion through hydro plants, taking into account their large initial investments.

We would like to address the following questions:

How do the authors expect the evolution of this methodology for dealing with stability problems and how to deal with uncertainties such as demand growth, interest rates and equipment construction times?

How is the generation indicative plan established?

Are many economic signals provided by the transmission entity, in order to obtain the reference generation expansion planning?

What are the discrepancies if any, between the reference generation plan and the actual generation expansion and how the transmission system is adapted?

In some cases a problem to supply some specific demand can be solved by adding new transmission facilities or small generation plants. How competition between generation and transmission facilities can be considered in the proposed framework?

Considering the fact that genetic algorithms converge slowly, do the authors think that this approach could be applied to a very large, or would it be necessary to improve the fitness function? (ref. [2]).


Dipl. Ing. Torsten Nikodem and Prof. Dr. Ing. Edmund Handschin (University of Dortmund, Department of Electrical Power Engineering, Germany): A transmission planning methodology for the Chilean and Peruvian deregulated open access environment is presented. The method is orientated towards the concept of an economically adapted transmission system implying that transmission planning is directly related to the economical concept of marginal pricing.

The authors show that the proposed usage of a genetic algorithm to solve this complex optimization problem is a useful approach. The main benefit of the application of the genetic algorithm is to be seen in the somewhat decoupled mathematical treatment of the planning and operation features by simulating the system operation for possible investment solutions and ranking the results obtained. The authors take advantage of this possibility by including features, partly previously developed, like hydrologic randomness into the simulation. Particularly, for the Chilean electrical energy supply with reservoirs having interannual regulating capacities this is a aspect of prime importance. Even though the transmission network is modelled using DC load flows reactive power compensation and associated operation criteria are also taken into account for a number of the best plans previously obtained. Unfortunately this aspect is only outlined. It would be interesting to know whether an optimal allocation of necessary compensation equipment is also included and whether the resulting costs are considered.

The developed computational method is applied to the main Chilean grid using a reduced network modelling eight buses. In this context, an analysis of the effect of the restrictions made, e.g. eight bus system with ten possible paths, four alternative investment schemes for each path, would be useful. Certain input quantities like fuel cost and load growth are associated with uncertainty in the considered time horizon of ten years. Studies on the influence of these uncertainties on the planning results and the costs obtained may be an issue of interest.

In summary, the presented methodology is likely to provide interesting results for transmission planning and also for pricing of electricity in the Chilean energy supply industry.

VLADIMIRO MIRANDA, L. M. PROENÇA, INESC - Inst. de Engenharia de Sistemas e Computadores and FEUP/DEEC - Faculdade de Engenharia da Univ. do Porto, PORTUGAL: We would like to congratulate the authors for the excellent paper presented; it shows once again the interest of investigating the potential of a tool like Genetic Algorithms in the field of Power System Planning.

However, the paper raises some questions concerning especially two aspects: the apparently exaggerated computation time and the small number of generations in the example presented. In this view, we would appreciate if the authors could provide us some enlightening about the following:

1 - Do the authors think that the small number of generations is enough to assure the convergence of the algorithm? Was the number of individuals in the initial population in some way optimized for performance (considering the trade-off between the population size and the number of generations)? We fear that with only 10 generations, the circulation of "genetic material" is somewhat limited, eventually making the process not too different from some form of random search.

2 - Do the authors have any evidence that the average quality of the population increases significantly with the evolution of the algorithm? This question arises from the fact that there seems to exist a only a weak physical relationship between the codification and the constraints and objectives associated with the expansion plan itself.

3 - Or, put in another way: do the authors believe the crossover mechanism is, in any way, useful in the genetic process? If not, the process would again be no better than a random search. Have the authors compared their algorithm with one of random search type?

4 - Are the total costs considered to be a mean probabilistic value, or is there any other form of evaluating the
impacts of uncertainty in the decision process?

We would like to encourage the authors to further investigate through the path they have followed namely finding ways of coding the problem into chromosomes that would be an implicit representation of a longer set of project characteristics, because we believe we share the authors view that it is presently one of the fruitful fields to be explored.

Manuscript received June 21, 1995.

Marciano Morozowski Filho and Gladis Schuch (Federal University of Santa Catarina - UFSC/LABPLAN, Brazil): The authors are to be commended by this timely and innovative contribution to the subject of power system planning in a competitive environment. Power system planning in a deregulated business environment poses new challenges to planners and investors, both public and private. These challenges are related to the planning process itself and to additional uncertainties due to competition between economic agents: producers, transporters and big consumers. The first challenge has been addressed, in the Chilean, Peruvian and Colombian systems, by defining an indicative plan. The concept of a economically adapted transmission systems is linked with the minimum cost transmission expansion plan, generated by a genetic algorithm, adapted to solve this complex optimization problem. In this context, we would appreciate if the authors could clarify the points that follows.

The first one relates to the hypothesis of absence of economies of scale in the integrated generation-transmission business. Is this hypothesis necessary to equalize short term and long term marginal costs? Are there evidences, in the Chilean or other systems, supporting it?

If there are positive evidences of it, is the linearity between investment and capacity maintained if the generation and transmission plans are separately developed, as is the case in the paper? Is the generation plan economically adapted?

The genetic algorithm is a new solution technique for large scale, non-linear optimization problems. However, it does not assure the optimality of the expansion plan. Are marginal costs meaningful in this case? We would appreciate the authors comments.

Manuscript received July 12, 1995.

J W Marangon Lima and A P Alves da Silva, Escola Federal de Engenharia de Itajubá (Brazil) - Many efforts have been devoted to the development of tools designed to solve the generation and transmission expansion problem in a centralized scheme. As stated in the paper, this is a complicated issue because of the many factors it has to consider. The complexity becomes even worse with the incorporation of a decentralized scheme which aggregates another degree of uncertainty related to the economic agent behavior. In this new economic environment, the role of the planning staff may be questioned given that the development of the generation and transmission systems is left to the market and private investors.

We would like to congratulate the authors for this paper which deal with this important subject. We would like to hear from the authors some comments about five points:

1. It is not clear from the paper how the generation-transmission indicative plan, provided by the regulators, works in a competitive and deregulated environment which is currently adopted in the Chilean and Peruvian electric systems. The acceptance by the economic agents of this adapted system which encompass the principle of social optimum may not be so obvious given that this plan can be against their individual goals. On what basis are the transmission planning conflicts settled?

2. The use of heuristic techniques, such as GAs, to design a generation-transmission plan seems to be a promising approach. However, for the Chilean system presented in the paper, it seems that an optimal method would be more effective. Besides, how the GA approach computing time will scale with system size?

3. As GAs are strongly affected by the coding scheme, it is not clear from the paper why the proposed code was selected? The sensitivities (Appendix A) used for creating expansion plans for the initial population are not being used to evaluate new populations, i.e., they are not included in the fitness function. Therefore, there is no guarantee that the subsequent generations will follow the sensitivities.

4. The paper does not mention if the problem constraints are added to the fitness function as penalties, or if the infeasible elements of a population are deleted. The discussers' experience with GAs indicates that the first option speeds up the convergence process.

5. It is not clear from the paper what is the influence of the two transmission pricing methods on the adapted expansion plan?

The improvement of optimization techniques and heuristic dynamic methods which can deal with all the transmission system features will yield important dividends for a better system planning. On the other hand, it may present some problems related to the necessity of transparent information to competitive parties. A better understanding by all parties of the transmission planning issues and the impacts of transmission pricing methods on the expansion plan seem to be the challenges for the near future.

Manuscript received August 17, 1995.

L.L. Lat* and R. Yokoyama, (Department of Electrical Engineering, Tokyo Metropolitan University, Tokyo, Japan): The authors are to be commended for presenting an interesting paper. We would like to offer the following comments on the paper:

The field of global optimisation has been rapidly expanding over recent decades, aiming at finding general search algorithms for cost functions with many local minima. The function can be non-differentiable and/or discontinuous. Most classical methods of optimisation generate a deterministic sequence of trial solutions based on the gradient or higher-order statistics of the cost function. Under normal circumstances, these techniques can be shown to generate sequences that asymptotically converge to locally optimal solutions. But the methods often fail to perform adequately when random perturbations are imposed on the cost function. In addition, locally optimal solutions often prove insufficient for real-life problems. It is now widely recognised that gradient-based non-linear programming techniques would typically fail in the above situations, and drastically different approaches need to be developed.

Recently, a global optimisation technique known as Genetic
Algorithm (GA) has become a candidate for many optimisation applications due to its flexibility and efficiency. GA is one of the stochastic search algorithms based on the mechanics of natural genetics. A solution variable for the problem is first represented using artificial chromosomes (strings). In other words, the problem is encoded to strings that GA can handle. A string represents one search point in the solution space. GA is a parallel search method because it uses a set (population) of strings (i.e. multiple search points). It modifies strings (searching points) using natural selection and genetic operations such as cross-over and mutation. After convergence, strings are decoded to the original solution variables, and the final solutions are obtained. It is clear that the decoding procedure is a very important step. What is the decoding procedure used by the authors?

Like other stochastic methods, the GA has a number of parameters that must be selected. One of the main problems in genetic algorithms is the occurrence of premature convergence. Premature convergence could be subdued by variations of operations such as crossover, selection, mutation and by alterations of parameters such as population size, crossover rate and mutation rate. In restricting the population size, the genetic operators may loose the optimal genetic material by placing it with sub-optimal material and eliminating it within the next generation. It is important to have enough genetic material and combinations of material in the initial population to examine the entire solution space in detail. It would be appreciated if the authors could explain the study for different population sizes.

The authors show that the performance of their approach could be much improved if the ‘evolution’ of the solution is not left entirely to chance but is guided towards the optimum with an engineering logic, based on electric sensitivities. This approach is again against the basic philosophy of genetic algorithms. It is likely that the final solution may actually be quite far away from the global optimum.

Simulated evolutionary optimisation is still in its infancy, yet it is expected to continue to grow in importance and practical benefit. As the availability of massively parallel processors becomes increasingly common, the value of the techniques will become more apparent. For this application, GA may not be the best choice from the Evolutionary Computing techniques, however, the authors have made one step forward in applying intelligent techniques to transmission planning.

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H. Rudnick, R. Palma, E. Cura & C. Silva (Universidad Católica de Chile, Santiago, Chile). We thank the discussers for their useful comments, which help us in the continuance of a fruitful area of research. They also provide us with the opportunity to clarify or expand some of the contributions of our work.

The discussions aim at two aspects: transmission planning and application of genetic algorithms. We will answer them separately.

**TRANSMISSION PLANNING**

i) Planning with competition: Discussers Vieira Filho, Gorestin & Pereira contribute with valuable comments on the concept of a centralized reference plan and the importance of adequate economic signals to market participants. We agree with them, and with Marangon-Lima & Alves da Silva, on the essential difficulty of planning in a market environment where competitors may have conflicting interests on power system development.

In Chile the regulator determines an economically adapted (EA) generation-transmission system ("the indicative plan"). This system is determined periodically by evaluating alternative investments in generation and establishing the plan with the least present cost. The regulator considers alternatives from a set of known available hydroelectrical sites, different size thermal plants and projects proposed by private investors. Given the Chilean radial network structure, new transmission investments have been always linked to specific generation plants. The total present supply cost is evaluated considering plant investment and cost of operation, the latter determined through a hydrothermal stochastic coordination model. Demand growth, fuel cost and interest rates are assumed known. The regulator then sets tariffs for small consumers based on a projection of spot prices within the indicative generation plan. Therefore, competing market players know the tariffs they will face in the future (for around 60% of the market) and react accordingly. This has meant in Chile that the actual investment plan for generation has followed closely the indicative plan, at most with private investors slightly delaying unit commission to maximize their income. Nevertheless, the arrival to Chile of natural gas pipelines and combined cycle units, plus foreign investors looking for lower rates of return, are changing the picture and there are evidences that the indicative plan may not be followed in the short term. However, the regulator must recognize private decisions and update the indicative plan accordingly.

In Perú, and in the recent Bolivian electricity law, the regulations go further, with the regulator not only determining an indicative generation plan and the spot price projection, but also limiting transmission income to an EA grid determined by the regulator. The challenge for the regulator is how to make that determination and the paper contributes to that objective by providing a systematic tool to evaluate it. Those regulations have not been in place long enough to provide practical experience of the kind inquired by Vieira Filho, Gorestin & Pereira and Marangon-Lima & Alves da Silva. Nevertheless, the question remains open on the potential conflicts that may arise in such arrangement between the State regulator and the private owner of the transmission grid.

ii) Uncertainties in planning: Vieira Filho, Gorestin & Pereira, Nikodem & Handschin and Miranda & Proença raise the question of uncertainties in planning. The authors model hydrologic randomness (as done by the regulator when determining the indicative plan) but do not take into account uncertainties in fuel cost, load growth, interest rates or construction times. Financial uncertainties and risks could be more important to model in a deregulated market. Genetic algorithms could easily incorporate scenario analysis and/or do multiple objective optimization and the authors are exploring this. "Minimizing the maximum regret" approaches are another avenue, the question being their conceptual relevance in a competitive environment where risk analysis is more relevant.

iii) Reactive power, stability and reliability: Nikodem &
Handschein raise the question of reactive power associated investment and its impact on planning. We propose to do an ex-post AC assessment of the best, say five, plans, re-ranking them according to the associated compensation costs. This could also be done in relation to the reliability of the determined transmission plans and the stability of the resultant systems.

iv) Generation-transmission planning: Our main contribution is in the development of a dynamic transmission expansion tool that can handle both short term generator operation costs with transmission investments on a long term scale. We have recently learned of related research activities, one using Benders decomposition in a stochastic approach [26] and the other using simulated annealing [27]. The first one optimizes the expansion of generation coupled to area interconnections, while the second only deals with static transmission planning.

Morozowski & Schuch raise the important question of economies of scale. While economies of scale are significant in the transmission business, the Chilean regulation was built assuming no economies in the integrated generation-transmission industry. This has been questioned by some utilities and simplified studies of the profit evolution of the integrated business contest that assumption. Proving the link with the short-term-marginal-cost=long-term-marginal-cost equation is further clouded by the discrete character of investments in the power system, where physical adaptation is seldom the case. In this field, the economically adapted concept could prove useful and we are presently studying the related economics in more depth. The discussers further ask about the linearity in separating generation and transmission planning. While we start from an economically adapted generation plan, we have no evidence on this linearity and clearly a GA that could optimize both in an integrated manner would be useful to test this. We acknowledge the certain condition raised by Vieira Filho, gorestin & Pereira where a load may be supplied either by adding new transmission facilities or small generation plants. An integrated GA search would be able to assess such situations and provide guidance. Alternatively, transmission pricing and allocation schemes (of the kind compared in the paper) could communicate economic signals to guide generator decisions, providing coherency to separated generation and transmission plans.

Morozowski & Schuch ask about the use of marginal costs in the optimization process. In our algorithm they are meaningful in the building of the set of plans that the GA uses as a starting point (the initial population). Sensitivities, used to build new plans for that population, are directly associated with the differences of marginal costs at the ends of each available path. A difference arises out of losses in the transmission line or in saturated conditions (the marginal revenue). The benefit/cost ratio index combines the marginal revenue with the investment annuity.

v) Production simulation: The model takes into consideration the operation patterns of one large multi-year hydro reservoir, several smaller reservoirs and run-of-river plants, as well as differences between coal plants and combined cycle gas units [28]. These patterns are coherent with procedures in effect in Chile today. Nevertheless, it must be emphasized that the simulation is approximate, given the planning time horizon.

In reply to Wong, a yearly planning interval was adopted, with three load levels and three hydrological conditions, although longer intervals can be used.

vi) Transmission cost allocation: The resultant allocation of transmission payments, given two different allocation methodologies, was shown as an example of the studies that can be made with the tool, most important in open access competitive environments. Figs. 8 and 9 are included to relate total collected payments with line costs and generator contributions. In reply to Marango-Lima & Alves da Silva, we are presently assessing economic impacts of transmission EA investment decisions on the generators and we will report at a later stage.

GENETIC ALGORITHM

We have concluded that important advantages of genetic algorithms for planning purposes are the possibility to easily link expert engineering criteria in the optimization process and to model strong nonlinearities.

Following we reply to GA questions by discussers Park, Wong, Marango-Lima & Alves da Silva, Miranda & Proença and Lai & Yokoyama. We thank them for better relating our work to other practical experiences with evolutionary computing techniques.

i) Comparison with conventional methods: We are not aware of other studies applying classical optimization methods to dynamic transmission expansion planning. As indicated, a recent related reference uses Benders decomposition [27] but solves a different problem. We did some basic assessment comparing dynamic transmission planning for a radial network using both a GA and a mixed integer branch and bound algorithm. As the time horizon and number of technological alternatives grew, GA proved faster (two times faster for a 100 integer variable planning problem). Basic comparisons were made with pure random search, which proved very time consuming and did not improve plans as GA did.

ii) Fitness function: The present value of operation and investment costs was minimized, which is equivalent to maximize its negative value. The GA tool used scales this value accordingly. Higher level functions are being explored.

iii) GA parameters: The parameters used for the reported example were: population size 400 members (empirically determined as the minimum required size for the Chilean network); 3000 members evaluated; no mutation; crossing rate 1 and a mask crossover operator (as explained next).

iv) Genetic operators: We do not use a traditional GA as quoted by Lai & Yokoyama, but what could be called an iterative heuristic GA. Fundamental is the use of a mask crossover operator that applied over the initial planning proposal insures the development of new feasible plans. This reduces the search space for the GA and does not require to incorporate problem restrictions in the genetic code. It is a
guided search based on expert criteria, where genetic material is circulated as required. Another contribution to guide population growth is the use of sensitivities in building the initial population. This initial group is built through a combination of pseudo-random operators to create new feasible plans and the use of sensitivities that modify the originally proposed plan (between 10 to 20% of the initial population is obtained with sensitivities, the rest with the pseudo-random operators). The authors believe that fast convergence is achieved because of the use of those sensitivities in building the initial population and the use of guided crossover operators. The use of pseudo-random operators contributes to avoid local sub optimum solutions.

We used sensitivities only in the building of the first generation, as we assessed that it would be at that stage where it would be most useful. As the GA progresses, new generations would be better adapted and no major changes would be introduced by sensitivities. However, we recognize that they could still contribute in the earlier stages.

v) Coding: The definition of the genetic code (chromosome elements) aimed at obtaining a clear and compact code with a modular simple structure to facilitate crossover operations and direct use of variables of the objective function. Actually, both the basic code and the crossover mask operator were built jointly. As indicated above, the problem restrictions are not included in the code but in the population building process, providing a filter in population growth. A symbolic genetic code was built, where binary numbers are used within a 16 bit string, but they really handle integer elements (all 16 bits are changed simultaneously rather than bit by bit). We explored other coding schemes but were satisfied with the one chosen. The code, the operators and the initial population strongly link the objective of investment cost reduction, the physical variables and the constrains.

vi) Convergence: We do not face convergence problems, given the initial proposed plan, the use of sensitivities and the guided crossover. We did face premature convergence problems at early stages of our research when using smaller populations. Tests were made to assess an adequate size for the given problem (the larger the population the better, but there is a limit given that the approach chosen to evaluate each member is very expensive time wise).

In response to Morazowski & Schuch, optimality of solutions obtained with a GA depend on population size, coding, crossover and mutation rates, number of generations, etc. The selected parameters proved useful for our planning purposes.

vii) Repeatability: Use of pseudo-random numbers assures that the same final point will be reached from one given starting point. Nevertheless, we have not tested using different seeds for the pseudo-random operators that create new feasible plans.

viii) Computation time: Since the paper was written, CPU time has been reduced through different changes. The nonlinear economic dispatch in the production cost simulation was replaced by a linear dispatch, reducing time by 75% (the linear dispatch is sufficient for planning on a long term horizon). Cluster distributed processing reduces CPU time by a factor almost equal to the number of CPUs (communication CPU time requirements are very small). Nevertheless, the cost of production simulation will remain the bottleneck in any approach.


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