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A Framework for Transmission Planning in a Competitive Electricity Market

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***Abstract*-- In this paper, a framework for optimal transmission system expansion planning in a competitive electricity market environment has been proposed. Open access transmission has created a deregulated power market and brought new challenges to system planning. The goal of transmission planning is to determine an optimal planning strategy for the transmission company. From the planner's view, planning is the process for balancing the multiple conflicting objectives with many constraints. The primary objective of transmission planning is to ensure the reliable supply to the demand as economically as possible. The new approach in this paper is formed to minimize the Expected Energy Not Supplied (EENS), investment cost and maximize the benefit-cost ratio λ subject to the power flow and security constraints. The computer program for reliability evaluation of bulk power systems CRUSE is used to perform reliability evaluation of the transmission system with predetermined outages. An advanced genetic algorithms (GAs) is utilized to solve the multi-objective optimisation problem. The advantages of the new approach include 1) it achieves the possible highest reliability with less cost; 2) it maximizes the cost efficiency, which increases the competitive advantage of a transmission company; and 3) the resulting plans contain the planner's preference which is easy to adjust. The planning approach has been illustrated on the Roy Billinton Test System (RBTS).**

***Index Terms* - Genetic algorithms, least-cost planning, reliability, risk analysis, and power system transmission planning.**

I. Introduction

As an essential part of energy planning, power system planning plays an important role in operating and competing in a deregulated electricity market. From the independent system operator's (ISO) perspective, power system planning must ensure the possible highest reliability in particular power system design. On the other hand, from the point of view of a market participant or an investor, power system planning needs balance between risks and return as well as enhancing their investment returns. The open access power system brings customer more benefits, and stimulates the participants to innovate and improve the efficient manner.

Traditionally the most widely practiced method for expansion planning is the least-cost planning (also known as integrated resource planning or integrated demand-supply planning). It minimizes the present worth of investment cost while meeting the design criteria. This method encourages utilities and consumers to change energy consumption patterns in order to reduce the overall costs, [1].

Since the last two decades, power industry around the world has been experiencing deregulations leading to competitive electricity market. As a result of the deregulation, new challenges have emerged in power system planning with regard to market constraints and increased uncertainties. There have been some new planning methods trying to meet such challenges, especially to handle the increased uncertainties, [2, 3] Most of these new methods try to minimize the total cost while meeting the system reliability requirement.

Based on the above considerations, transmission expansion planning is presented as a constrained multi-objective optimisation problem and can be solved by heuristic optimisation methods such as GAs. In the proposed methodology, the reliability is evaluated in terms of EENS and market costs including customer outage cost, construction cost, operational and maintenance cost. Case studies of planning with the proposed method are presented in this paper to demonstrate the effectiveness of the method.

II. Overview Of The Transmission Planning

A. Power system planning

In a regulated environment, the objective of transmission planning is to ensure the system reliability as high as possible. Relatively less economic concern is paid in the planning process compared with that of a deregulated environment, because planners are usually not worried much about how to cover the investment. The planners are able to generate alternative expansion plans based on all available historical data. The optional plans will then be tested by different system scenarios to fulfil other objectives and concerns in planning. The accepted robust plans should be able to supply the load reliably under all the scenarios and considerations. The planner selects the relative least cost plan among the robust ones as the final expansion plan. Obviously, this approach results in a very reliable system but not necessarily a cost-effective one.

In a deregulated environment, competition is introduced to create a competitive electricity market. Accordingly, planners need to deal not only with the system reliability constraints but also the economic and financial limits. In a competitive

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electricity market, power system planning is no longer a schedule; instead, it is an expansion strategy. Good expansion plans can help the service provider/asset owner move to a favourable position for competition.

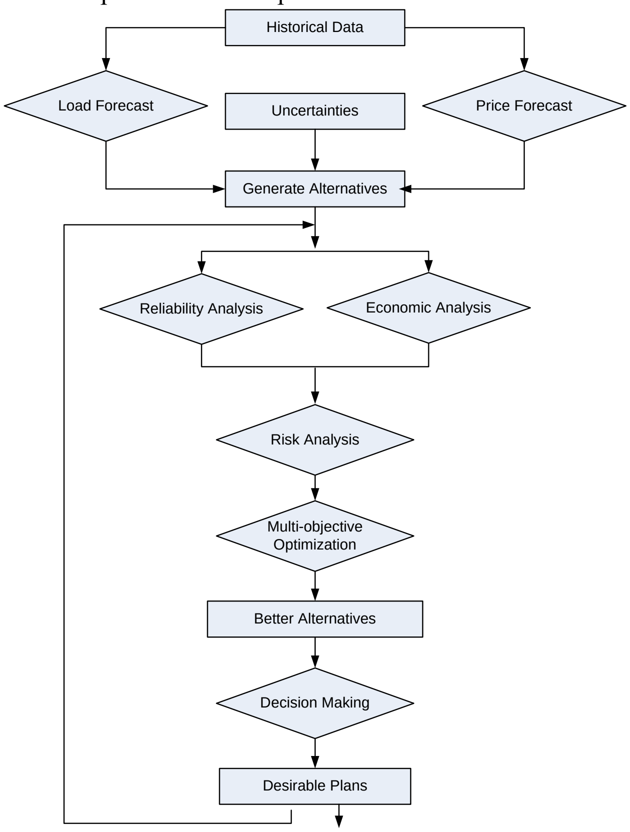

Figure 1 General Framework of Planning

A general framework of planning in a competitive electricity market is proposed ,which is shown in Figure 1. From historical data to final desirable plan, it covers technical and economic / finance analysis. Demand forecast and price forecast are important parts of expansion planning for this framework. However, there are many load and price forecasting techniques, [5, 6] with high accuracy and level of confidence. They can be readily used for this framework and will not be detailed in this paper.

B. Power system reliability

Reliability can be seen as the degree of assurance in providing the customers with continuous service of satisfactory quality. Power system reliability can be divided into two aspects, adequacy and security. Adequacy is associated with static conditions, which do not include system disturbance. On the other hand, security relates to the ability of the system to respond to disturbances arising within that system [7]. It is easier to obtain the input data to calculate adequacy indices than security ones. Present reliability evaluation techniques generally relate to the assessment of adequacy [7]. A lack of running generation capacity can break down the balance of supply and demand. This will lead to load shedding. Same as generation, the limited transport capacity will result in over-load. In a word, better power system reliability assessment provides more effective solutions to minimize the probability of system blackouts.

C. Economic / Financial analysis

The massive budget for system to keep enough operating reserve capacity no longer exists in a competitive market. New investment is usually evaluated through profits rather than meeting public service needs in a competitive market. The investors not only think about the cost, but also how much return they can get from the investment. Consequently, the ratio of benefit/cost is a significant planning index in a market environment. In our framework, cost includes direct and indirect cost. It should be noted that the indirect costs could be considerably higher than direct costs [9].

In competitive markets, reliability can also be measured by economics aspect. Such as the economic losses experienced by different sector customers resulted from the reliability problems can be presented by Customer Damage Functions (CDF), which has been widely used to evaluate the reliability worth, [10, 11]. Reliability can easily be expressed by financial penalty of failing to supply.

D. Uncertainties

Knight defined his famous definition of uncertainty in [13], where uncertainty means randomness with unknowable probabilities. Uncertainties in power system planning include weather, demand growth, fuel costs, construction time, market impact, social environment, economic growth, behaviour of other participants, etc.

More uncertainties have emerged because of deregulation and imposed more requirements for system planning. The new uncertainties may come from the demand side or from the industry participants. Because the electric utilities are no longer monopolies, demand side creates more uncertainties than ever. Customers can choose whatever supplier they want instead of the one which have been planned before in a regulated environment. On the other hand, the new uncertainties can result from the bilateral contracts between utilities. The bilateral transaction may lead to overload on a particular transmission line. It is clear that overloads should be avoided because they may cause blackouts. In order to make the right decision, uncertainties must be taken into account by using decision analysis. It is difficult to enumerate all the uncertainties, so the method to make a robust plan is what we proposed in the general framework.

E. Decision making

Most transmission facility is designed for long lifetime. Any unexpected changes may happen during this period. Once starting to build, investors have to live with their decision over the planning horizontal years. The results of wrong decision may be disastrous. Therefore, the investment decisions are the essential part for transmission expansion planning.

Decision theory has been used by electric utility to deal with uncertainties in order to minimize the risk. It is possible to take all relevant factors into account when making decisions, by using probabilistic measures to quantify them.

Some considerations have traditionally entered into the decision process which includes cost minimization, technological risk, local economic consideration, as well as financial, ecological, and regulatory issues [1].

III. Market Oriented Composite Transmission Expansion Planning Method

A. The objective function

Power system planning is a problem which requires solutions of the objectives of different social groups such as the investors, customers, employees and so on. The objectives are often conflicting. The multi-objective optimization method is employed to achieve the best solution as close as possible to the Pareto-optimal front [16]. The objective function of transmission planning process is given in (1) – (4) and the constraints including power flow constraints and various limits are given in (5) – (9).

Min $$COST = C^T\eta_{mn} + \sum_g V_g \cdot G_g + COCs \quad (1)$$

Max $$\lambda = \frac{TC \cdot \sum_i c_i \cdot l_i \cdot F_{i,t}}{COST \cdot \sum_t \sum_i c_i \cdot l_i \cdot F_{i,t}} \quad (2)$$

Max $$\Delta EENS = EENS_o - \sum_{j \in LC} L_{kj} \cdot D_j \cdot f_j \quad (3)$$

Max $$\Delta COCs = COC_o - \sum_{j \in LC} L_{kj} \cdot C_{kj} \cdot f_j \quad (4)$$

Subject to

$$P_i - V_i \sum_{j=1}^{j=n} V_j (G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij}) = 0 \quad (5)$$

$$Q_i - V_i \sum_{j=1}^{j=n} V_j (G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij}) = 0 \quad (6)$$

$$P_{\min} \le P \le P_{\max} \quad (7)$$

$$Q_{\min} \le Q \le Q_{\max} \quad (8)$$

$$V_{\min} \le V \le V_{\max} \quad (9)$$

where

C^T: Construction cost of transmission line

V_g: The variable cost of plant *g*.

G_g: The expect generation of plant *g*.

c_i : The cost per MW per unit length of the line ($/MW-mile)

l_i : The length of the *i*th transmission line (miles)

$F_{i,t}$: The maximum flow on the transmission facility *i* caused by the transaction *t*

η_{mn}: New transmission lines from bus *m* to bus *n*

L_{kj} : Load curtailed at bus *k* due to contingency *j*

D_j : Duration (hours) of load curtailment due to contingency *j*

C_{kj} : Outage cost at bus *k* from contingency *j* with outage duration D_j

f_j : Frequency of occurrence of outage *j*

$EENS_0$ and COC_0: Excepted energy not supplied and customer outage cost of original system

TC: Total cost of all lines in $, it may include running cost, past capital investment, and ongoing investment for future expansion and reinforcement associated

λ : the benefit-cost ratio.

B. Hypothesis

The priority of the proposed transmission planning method is to design the system reasonably with sufficiently detailed analysis to reflect the actual complexities. Some important points for this study are:

1. In order to see the difference which only results from transmission line, it is assumed that the generation system is reliable; therefore, there is no contingency at generation level
2. It is assumed that branch overloads are dealt with by rescheduling and load shedding.
3. The load duration curve that has been used in this paper is given in Figure 2

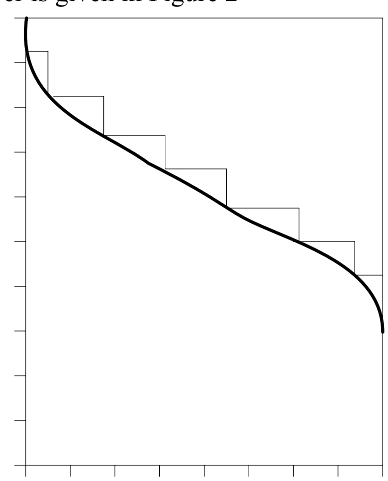

Figure 2 Load duration curve for the RBTS ([17])

C. The key issues in the method

1) Reliability analysis

In a deregulated environment, system equations will be handled by the ISO. Their objective is to minimize flow violations indicated by EENS. Accordingly, EENS, which was a constraint in a vertically integrated utility model, has turned out to be the ISO's objective in restructure power systems [4]. EENS has been used as the index of system reliability in the framework.

2) Reliability cost and reliability worth assessment

In a competitive market, the assessment of reliability cost/benefit is more significant. The COC at a load point *k* e can be calculated by using the interruption durations and the Composite Customer Damage Function (CCDF) as shown in Figure 3. The CCDF can be produced by aggregate of the sector CDFs. It shows the relationship between Interruption Cost and Interruption Duration at each particular load point. The average failure rate and the average duration of interruption have been given in [17].

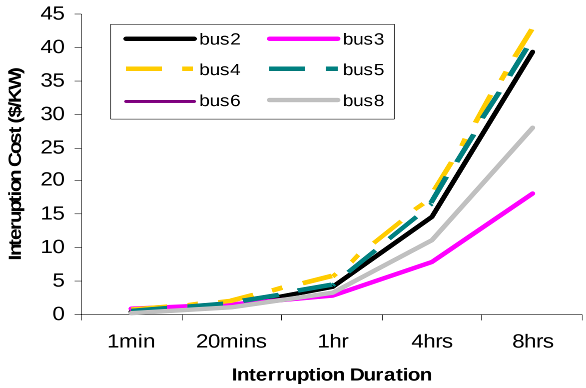

Figure 3 Composite Customer Damage Function for Each Bus

3) Economics analysis

From the investors' point of view, both cost and benefit are important factors. In this paper, benefit to cost ratio λ is used to reflect the cost efficient. At the same cost level, λ increases with benefit.

- **Cost**

The total cost is the combination of construction cost, operation and maintenance cost and customer outage cost. The construction cost of transmission lines have designed carefully (see Appendix). For each COCs, all possible contingences have been considered.

- **Profit**

Transmission pricing are the overall processes of translating transmission costs into overall transmission charges [18]. TRANSCOs get their profit through transmission charges. Power flow based MW-mile methodology was used to get the transmission pricing. This transmission cost allocation method considers changes in MW transmission flows and transmission line lengths in miles [19].

$$TC_t = TC \times \frac{\sum_j c_j * L_j * F_{j,t}}{\sum_t \sum_j c_j * L_j * F_{j,t}} \quad (10)$$

where TC_t is cost allocated to transaction *t*, L_j is the length of the line in miles and c_j is the cost per MW per unit length of the transmission line ($/MW-miles). The profit covered all lines in transmission corridors.

D. Genetic algorithms

The proposed planning approach is a complex optimisation problem. Traditional optimisation method may face difficulty dealing with possible non-convexity and discontinuities. GAs has been used as an optimisation tool to solve this problem, which are based on the mechanics of natural selection and natural genetics. Over the last decade, GAs have been extensively used as search and optimization tools. It is good at finding "acceptably good" solutions with "acceptably quick" time. In this paper, binary genetic algorithms as multi-objective optimization tool are utilized to solve the problem, which has following features, [8, 16]:

- Fitness function, which depends on the objective function given in Equations (1-4).
- Reproduction mechanism determines which strings are selected. Higher performers will be selected more often then lower performers.
- Crossover mechanism to combining parent chromosomes to produce children chromosomes. Crossover combines the "fittest" chromosomes and passes superior genes to the next generation.
- Mutation mechanism altering some genes in a chromosome. It ensures the entire state-space will be searched, (given enough time) and can lead the population out of a local minima.

E. Risk Analysis

Because there is no guarantee that GAs can find the absolute optimal solution [3, 8] and because of other uncertainties in planning, Risk analysis (RA) is used to help the planner to make a final decision. Under the risk analysis paradigm, the preferred solution will be selected by using Minimax regret criterion. The Minimax regret criterion focuses on avoiding regrets that may result from making a non-optimal decision. Regret is defined as the opportunity loss to the decision maker if action alternative A_i is chosen and state S_i happens. In proposed method the plan that minimizes the maximum weighted regret over all futures will be selected as the final plan ($\underset{i}{Min}\{\underset{k}{Max}\{w_k(f_{ik} - f_k^{op})\}\}$). The regret of solution *i* in future *k* is $f_{ik} - f_k^{op}$. f_k^{op} is the cost of i^{th} solution in future *k*. f_k^{op} is cost of the optimal solution for scenario *k*. More details on risk analysis can be fund in [4, 15].

IV. Case Study

Composite Reliability Using State Enumeration (CRUSE) [20] developed by Powertech Labs Inc. is a computer program for reliability evaluation of bulk power systems. Most traditional reliability indices and reliability worth indices can be calculated easily. In this paper, CRUSE is used to obtain the expected energy not supplied and customer outage cost.

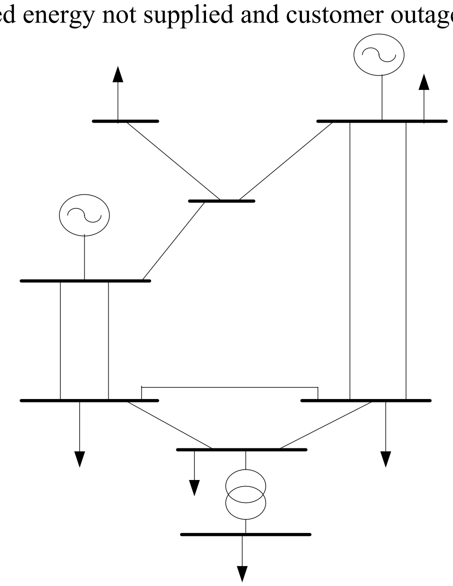

Figure 4: The Modified RBTS System

Case studies of transmission system planning are carried out using the proposed planning framework on the modified RBTS – as shown in Figure 4. It contains 2 generator buses, 11 generating units, and 11 transmission lines.

The original load is expected to increase 100% over the planning horizon year (10 years). In order to meet the demand increase, new transmission lines have to be added to ensure reliability and to meet other objectives as defined in (1)-(4). Four strategies are obtained under four scenarios:

Opt. 1: 3 new lines are added between bus1 to bus 3.

Opt. 2: add 2 lines between bus 1 to bus 3, and add another 2 lines between bus 2 to bus 4.

Opt. 3: Adding one line between bus 3 to bus 5 base on Opt. 1.

Opt. 4: Adding one line between bus 3 to bus 5 base on Opt. 2.

Two of the four options are shown in Figure 5.

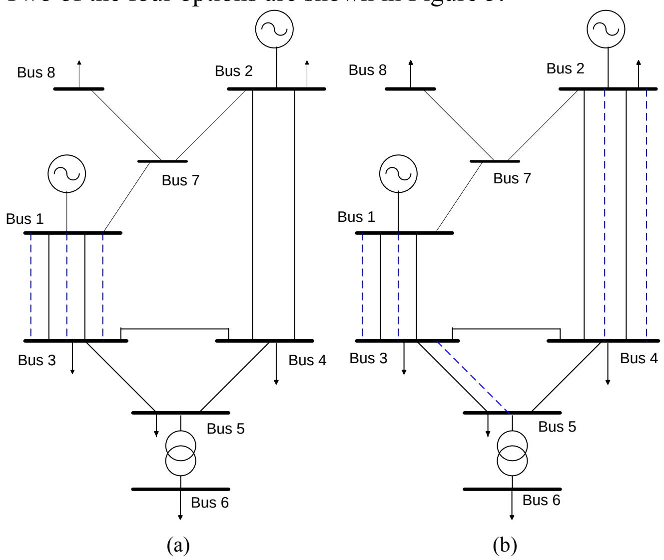

Figure 5: (a) Planning option 1 and (b) planning option 4 where the dotted lines are new transmission lines to be added to the system.

TABLE I: PLANNING DATA FOR THE TEST SYSTEM

	Option 1	Option 2	Option 3	Option 4
EENS (kWh)	63086.052	51027.534	61353.806	49829.628
COCs (k$/yr)	26459.14	24115.98	26080.19	23685.68
COST (K$)	157461	193280	161159	196721
λ	1.16398	0.950324	0.860807	0.911007

The corresponding reliability and cost information is given in Table 1. From table 1, it can be seen that the four objectives have different units and magnitudes. In order to get reasonable results, normalisation has to be performed to ensure the GAs return reasonable solutions. This is achieved in fitness function as shown in (11),

$$f(x) = \omega_1 \frac{1}{f_1(x)} + \omega_2 f_2(x) + \omega_3 f_3(x) + \omega_4 f_4(x) \qquad (11)$$

Where:

$f_1(x) = COST$, $f_2(x) = \lambda$, $f_3(x) = \Delta EENS$, $f_4(x) = \Delta COCs$, ω_i (i = 1, 2, 3, 4) is the weighting factors which enables normalisation as well as reflects the planner's preference.

$\omega_1 + \omega_2 + \omega_3 + \omega_4 = 1$

The results of optimization function is shown in Figure 6, from top to bottom it is the Maximum, MEAN, Minimum and standard deviation of fitness values. At generation 50, the mean value of fitness has nearly achieved the best fitness value. The optimal plan obtained from the optimization function is Option 4, which achieved the lowest EENS and COCs.

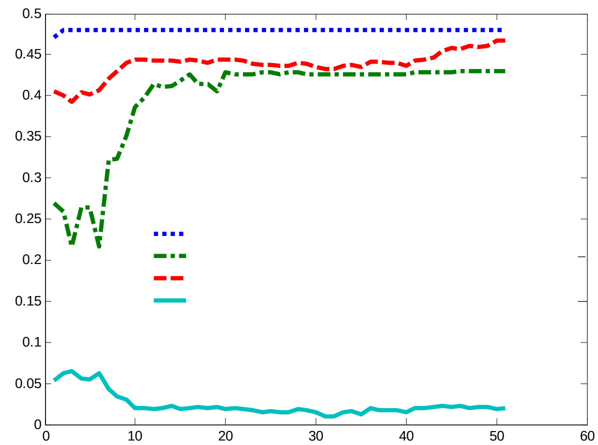

Figure6: The GA search statistics

TABLE II: PAYOFF TABLE FOR OPTIONS

Alternatives	States		
	Load increased 100%	Load increased 50%	Load increased 0%
Option1	127.49	36.82	6.89
Option2	127.78	36.62	6.88
Option3	128.65	36.72	6.87
Option4	129.69	36.92	6.85

TABLE III: REGRET TABLE

	Future Activity Regret			
Alternatives	Load 100%	Load 50%	Load 0%	Maximum (row)
Option1	2.2	0.1	0	2.3
Option2	1.91	0.3	0.01	2.22
Option3	1.04	0.2	0.02	1.26
Option4	0	0	0.04	0.04

By using minimax regret criterion, the payoff table has been shown as Table II. A payoff table is the means of organizing a decision situation, presenting the payoffs from different decisions given the various states of nature [14]. Table II presented that the future return under three different states, the load increased 100% in the next 10 years, or it may only increase 50% or even keep fixed. It is assumed that the rate of each state occurrence is 70%, 25%, and 5% respectively.

The maximum weighted regret of each future state is carried out by using $\underset{k}{Max}\{w_k(f_{ik} - f_k^{op})\}$. Such as the maximum regret of option 1 at load increase 100% state can be calculated as following:

Max {127.49, 127.78, 128.65, 129.69} - 127.49=2.2

The Table III has presented the detail regret value of each state. After using the RA, the option which has minimum value of maximum weighted regret will be chosen. In this case study, Option 4 has been chosen as the best plan which can fit the load environment with minimum regret. Decision maker now can get a clear idea that the Option 4 has more energy than others.

V. Conclusions And Future Research

A new power system expansion planning framework suitable for a competitive electricity market has been proposed. The main objectives of planning with this framework is a combination of optimisation problems including minimization of the EENS and investment cost, and maximization of the benefit-cost ratio λ, subject to the power flow and various planning constraints. The advantages of the new approach are 1) it achieves the possible highest reliability with less cost; 2) it maximizes the cost efficiency, which increases the competitive advantage of a transmission company; and 3) the resulting plan contains the planner's preference which is easy to adjust. The framework is applied to a test system and the simulation results have shown the effectiveness and robustness of the new planning approach.

Currently, the objective of power system planning is to serve load reliably and economically. In the future, flexibility will attract more attention because of the increasing uncertainties. As continuing research effort, the flexibility evaluation will be added in this method as an objective, which can measure the transmission network expansion flexibility.

VI. Appendix

TABLE IV The Construction Cost From Bus To Bus (M$)

	1	2	3	4	5	6	7	8
1	0	0	8.389	0	0	0	11.185	0
2	0	0	0	27.962	0	0	11.185	0
3	8.389	0	0	5.592	5.592	0	0	0
4	0	27.962	5.592	0	5.592	0	0	0
5	0	0	5.592	5.592	0	5.592	0	0
6	0	0	0	0	5.592	0	0	0
7	11.185	11.185	0	0	0	0	0	11.185
8	0	0	0	0	0	0	11.185	0

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VIII. Biographies

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