NATIONAL MAGLEV INITIATIVE - CALIFORNIA LINE
ELECTRIC UTILITY POWER SYSTEM REQUIREMENTS

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SUMMARY

The electrical utility power system requirements were determined for a Maglev line from San Diego to San Francisco and Sacramento with a maximum capacity of 12,000 passengers an hour in each direction at a speed of 300 miles per hour, or one train every 30 seconds in each direction. Basically the Maglev line requires one 50-MVA Substation every 12.5 miles. The need for new power lines to serve these substations and their voltage levels are based not only on equipment loading criteria but also on limitations due to voltage flicker and harmonics created by the Maglev system. The resulting power system requirements and their costs depend mostly on the geographical area, urban or suburban with "strong" power systems, or mountains and rural areas with "weak" power systems. A reliability evaluation indicated that emergency power sources, such as a 10-MW battery at each substation, were not justified if sufficient redundancy is provided in the design of the substations and the power lines serving them. With a cost of $5.6 M per mile, the power system requirements, including the 12-kV DC cables and the inverters along the Maglev line, were found to be the second largest cost component of the Maglev system, after the cost of the guideway system ($9.1 M per mile), out of a total cost of $23 M per mile.

INTRODUCTION

Southern California Edison Company (SCE) has conducted a Study to determine the route and the electric utility power systems requirements for a Maglev line in California. This work was performed as an input to the Maglev System Concept Definition Final Report which was issued on September 30, 1992 by a team headed by Bechtel Corporation, under one of the four National Maglev Initiative Contracts.

MAGLEV LINE ROUTE

As shown by Figure 1, the route selected for the Maglev in California maximizes the potential ridership by connecting the largest urban areas which have the following population projections for year 2000, based on Reference 1 :

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Urban Area	Population Projection (Year 2000)
Los Angeles	16.7 M
San Francisco	6.9 M
San Diego	3.0 M
Sacramento	1.8 M
Bakersfield	0.7 M
Fresno	0.7 M

Because Maglev can utilize elevated guideways installed on the median lane of existing freeways or highways, to minimize the need for land or right-of-way, the selected Maglev route follows Interstate 5 and Freeway 99 from San Diego to San Francisco and Sacramento, and Freeway 101 between San Francisco and San Jose, with two alternatives between the San Joaquin Valley and the San Francisco Bay area through the coastal mountains : the Altamont Pass Alternative on Freeway 480 and the Pacheco Pass Alternative on Highway 152.

MAGLEV SYSTEM DESIGN

The Maglev System, considered for the California line, is designed for the maximum capacity of 12,000 passengers an hour in each direction at a speed of 300 miles per hour, or one train every 30 seconds in each direction. The Maglev design characteristics, provided by Dr. Richard Thornton of MIT, are as follows :

The Maglev vehicles, which have been called "Boeing 737 without wings, tail, or engine", have a speed of up to 300 miles an hour, and are maintained by magnetic levitation at about 10 inches above a Guideway without physical contact. They do not require steel wheels and rails. Their propulsion system is of the repulsion or electrodynamic superconductive type; it consists in a Linear Synchronous three-phase AC Motor.

The stator coils, installed in the Guideway, create a magnetic field which moves along the Guideway at a speed which is a function of the AC frequency. The Rotor coils installed aboard the Maglev vehicle create another magnetic field. Interaction of the two magnetic fields provides propulsion and levitation. To minimize the weight of the rotor and maximize the gap between the Maglev vehicle and the Guideway the rotor coils are superconductive.

The resulting electric load requires a Substation every 12.5 miles along the route.

As shown by Figure 4, each Substation, served by the local electric utility AC power system, converts the AC to + - 12 kV DC with 12-pulse Transformer/Rectifiers . The DC power is delivered to two 12-kV DC cables which follow the Maglev line.

Every 2.5 miles, these 12-kV DC cables serve an Inverter which converts the DC back to AC, feeding the Stator coils of the Linear Synchronous Motor in the Guideway. The Inverter provides

adjustable frequency and voltage which control the speed of the Maglev vehicles. The Stator coils in the Guideway consist of independent 2.5-mile continuous blocks of coils, each served by an Inverter.

Each Substation has a peak balanced three-phase load of 60 MW (short time) and 50 MW (sustained), with power fluctuations of up to 40 MW every 30 seconds. These fluctuations are caused by the fact that the load of each Maglev vehicle is moving from one guideway stator coils block to the next. It should be noted that regenerative braking is possible with the regenerated power being delivered to the 12-kV DC Cables.

In addition to these power fluctuations, the Substation load includes voltage harmonics of 60 Hz, which are created by the rectifiers and inverters of the Maglev system and are propagated throughout the power system.

ELECTRIC UTILITY POWER SYSTEM REQUIREMENTS

All the electric utility power system requirements were based on Conceptual Planning, without benefit of computerized system simulations (load flow, short circuit, or stability), or detailed comparisons of alternatives, etc... However, this planning was done with the cooperation and the approval of the System Planning Departments of all Electric Utilities involved : San Diego Gas and Electric (SDG&E), Southern California Edison (SCE), Los Angeles Department of Water and Power (LADWP), and Pacific Gas and Electric (PG&E).

Reliabilty Criteria

The power system, required to serve the Maglev Substations, was designed to provide single contingency capability, with two lines on separate right-of-ways and two redundant transformer/rectifiers.

With this design, the risk of losing service to a Maglev Substation is very low : once in 25 years for 14 to 22 minutes, as indicated by a reliability study which was conducted by using the outage rate frequency and duration method (Reference 3). The study was based on the results of a statistical analysis of a 17-year outage history of SCE Transmission and Transmission Systems, published in a 1980 IEEE Paper by P. Save de Beaurecueil (Reference 4).

Therefore, the single contingency criteria provides an acceptable level of reliability and use of emergency sources of power such as a 10-MW battery at each Substation is not justified, especially when considering the exorbitant costs of batteries of this size. (These batteries were initially considered to allow Maglev vehicles to operate at reduced speed and unload passengers at the next Station, following a power outage of several hours, which is extremely unlikely.)

Maglev Substation Design

The design of a Maglev Substation is shown by the schematic one line diagram in Figure 5. The Substation includes two redundant 50 MVA transformer/ rectifiers, each one with two 12-kV windings, wye and delta, serving two six-pulse rectifiers in series, equivalent to a 12-pulse rectifier. Having only one transformer/rectifier with a few mobile spare units on trailers for the total Maglev line was not selected because transportation and connection of a mobile unit would take more than a day, which is not acceptable. The Substation line and bus on the transmission or subtransmission side is a ring bus with two-line service and two double-breaker line positions.

The rectifiers are connected to the 12-kV DC cables with two 4000-A DC breakers. These breakers are normally closed.

All Maglev substations have an outdoor construction design except three Substations (Numbered 1, 42, and 52 in Figure 2), located in downtown areas of respectively San Diego, Sacramento, and San Francisco, which have an indoor SF6 gas insulated substastion (GIS) design.

Service to Maglev Substations

The 50-MW peak load of the Maglev Substation has the same order of magnitude as the load of typical Electric Utility Distribution Substations which are normally served from the Subtransmission System (66, 69, 115, or 138 kV). However, because the Maglev Substation load can experience periodic power fluctuations of up to 40 MW every 30 seconds, and includes voltage harmonics, special evaluations are required to ensure that the Electric Utility power systems are not adversely affected. As a result of these evaluations, service from higher voltage (230 kV) systems and harmonics filtering may be required. These evaluations were conducted at the conceptual level in the SCE Study presented later in this paper.

As required for Electric Utility distribution substations, the power factor of the Maglev Substation load should be unity. This requirement is especially important in areas where the utility power system is not strong such as in the mountains or the rural areas of the San Joaquin Valley.

Substations with 50-MW loads such as the Maglev Substations can be served from the Subtransmission (66, 69, 115, or 138-kV) systems when these systems are sufficiently strong, which is the case from San Diego through the Los Angeles Basin and in the San Francisco Bay Area.

However, in the coastal mountains north of Los Angeles, and some rural areas of the San Joaquin Valley, service from the 230-kV Transmission System is required. In these areas, also, the existing 230-kV system needs to be reinforced by forming new 230-kV lines or upgrading existing 230-kV lines.

The Maglev Line, and the locations of the Maglev Substations, numbered 1 through 61, are shown by an overall map in Figure 2 and one out of four detailed maps in Figure 3C. The maps show the 500-kV and 230-kV transmission systems in the vicinity of the Maglev Line, including the new and rebuilt 230-kV lines required to serve the Maglev Line. For the sake of clarity these Figures do not show the subtransmission line additions.

Service From the Subtransmission System

Typically, Subtransmission systems feeding a certain number (between 5 and 25) of subtransmission substations are interconnected. Each Subtransmission System is served by a "Source" Transmission Substation which is supplied from the Transmission System (at 230 or 500-kV).

When service to the Maglev Substations is provided from the Subtransmission System, to minimize the impact on the local subtransmission system, the Maglev Substations are served by two "Source" subtransmission single-circuit lines on separate right-of-ways, which are directly connected to the closest Transmission Substation, "Source" of the local subtransmission system.

The new subtransmission lines are connected to the subtransmission bus of the "Source" substation with two separate double-breaker positions. When more than one Maglev substation is connected to a "Source" Transmission Substation a new Standard 168/224/280-MVA Transmission Transformer Bank was added to meet the additional substation load at the subtransmission level. The Transformer Bank was connected to both transmission and subtransmission buses with double breaker positions.

In the Los Angeles Water and Power Department Service territory , because only distribution voltage of 33 kV is available at Velasco, Toluca, and Sylmar Substations, two 230-66-kV 50-MVA transformer banks were provided at each of these substations to serve the Maglev Substations at 66 kV, to maximize the short circuit duties (as required to minimize the effects of harmonics and power fluctuations).

In the San Diego Service territory additions of Maglev Substations require rebuilding the San Mateo-San Luis Rey 138-kV line.

To provide higher reliability and more acceptable visual impact, the new overhead subtransmission lines directly connected to the Maglev substations are on Steel Poles instead of wood poles or lattice towers.

In some areas underground Subtransmission lines were planned, wherever there is public opposition or impossibility of having new overhead subtransmission lines, such as Orange County, or Downtown areas of San Diego, Los Angeles, San Francisco bay area, and Sacramento.

Service From the 230-kV System

Service from the 230-kV System was required in the rural mountainous and the San Joaquin Valley, by forming the following new 230-kV single circuit lines :

SCE	Pardee-Magunden (68.7 mi.) looped into Substations 15 and 16
SCE	Magunden-Rector (83.1 mi.) looped into Substations 23 thru 26
PG&E	Bellota-Wilson (64.0 mi.) looped into Substations 34 thru 37
PG&E	Legrand-Los Banos (44.0 mi.) looped into Subs. 55, 56, and 57.(Pacheco Pass Alternative)

The following double circuit 230-kV lines need to be upgraded :

SCE	Rector-Big Creek 1 and 3 (64.3 miles)
PG&E	Legrand-Gregg 1 and 2 (32.0 miles)

To provide higher reliability and more acceptable visual impact, the new overhead transmission lines directly connected to the Maglev substations are on Steel Poles instead of wood poles or lattice towers.

Maglev Substation Load Fluctuations and Harmonics - Evaluation

Contrary to the conventional electric trains, which are single-phase loads, Maglev systems have the advantage of being balanced three-phase loads. However Maglev loads still have the problems created by harmonics and periodic power fluctuations which cause voltage flicker. Evaluation of these problems was conducted based on the criteria described below. Although this criteria is not a part of the official SCE Transmission Planning Guidelines (Reference 2), it is considered to be reasonable and sufficiently conservative, especially for a conceptual study.

Voltage Flicker Criteria

Voltage Flicker, caused by power fluctuations, is inversely proportional to the Short circuit duty, as shown in a later paragraph.

Guidelines for Voltage Flicker have been used in the Power Industry for more than 25 years. As shown by Figure 6, typically, these Guidelines include two curves defining voltage flicker limits in percent voltage dips as a function of the flicker frequency : a Lower Limit, the "Border Line of Visibility", and an Upper Limit, the "Border Line of Visual Irritation". It consists of three sections:

1. Frequencies higher than 3 per minute : Border line of Visual Irritation.

2. For frequencies between 3 per minute and 10 per hour : 1.5 percent.

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3. For frequencies lower than 10 per hour : 2 percent.

This criteria should be met at least at the Point of Connection with the Electric Utility during minimum short circuit duty conditions.

Harmonics Voltage Criteria

This Criteria,shown in Table 1, is derived from Guidelines used by the French Electric Utility E. D. F (Reference 5). It has been applied for the loads of electric trains which have been in service for more than 50 years. They have been applied in particular to the latest "TGV" trains which have loads similar to the Maglev loads in terms of magnitude and harmonics, since they use AC induction motors with adjustable speed drive systems (Reference 6).

For Transmission or Subtransmision loads the criteria is as follows :

1. If the load creating voltage harmonics is below 1 percent of the minimum short circuit MVA duty at the point of connection with the Utility, it is acceptable and no further study or filtering is required.

2. If the load creating voltage harmonics is 1 percent or more of the minimum short circuit MVA duty at the point of connection with the Utility, a harmonics study is required to determine the harmonics rates for each rank (multiple of the 60 Hertz fundamental frequency). If the rates are found to be exceeding the limits shown in Table 1, filtering should be provided to obtain voltage harmonics rates within these limits.

Application of Voltage Flicker and Voltage Harmonics Criteria

Using the above criteria, the impact of the Voltage Harmonics and the Voltage Flicker, caused by the Maglev Substations loads, was evaluated for each Connection Point of the Maglev Substations to the Electric Utility Systems.

For each Maglev Substation, served from the Subtransmission System, the Connection Point is the Subtransmission Bus at the "Source" Transmission Substation to which the two subtransmission lines, serving the Maglev Substation, are connected.

For the Maglev Substations, served from the Transmission System, the Connection Point is the 230-kV Bus of each of the two Transmission Substations where the 230-kV line serving one or more Maglev Substations is connected.

The minimum short circuit duty, required for the evaluation of both voltage harmonics and voltage flicker, as indicated above, was determined as follows : First, the maximum short circuit duty (MVA and angle) at each Connection Point was obtained from existing short circuit studies. The minimum short circuit duties were then estimated to be a fraction of the maximum duty.

For the Connection Points in the 230-kV system : 50 percent in the San Joaquin Valley and mountainous areas, and 60 percent in the Los Angeles Basin or the San Francisco Bay area. For the Connection Points in the Subtransmission System : 90 percent.

Harmonics Voltage Evaluation

The need for detailed Harmonics Analysis and possible filtering was identified whenever the Maglev Substation load is 1 percent or more of the minimum short circuit duty. For the recommended service voltage level, all Maglev Substations require Harmonics analysis and possible filtering, except 6 Maglev Substations out of a total of 52 for the Altamont Pass Alternative, or 55 for the Pacheco Pass Alternative.

These findings are confirmed by the fact that TGV traction systems, which are similar harmonics characteristics, are provided with harmonics filters as indicated in Reference 7.

Voltage Flicker Evaluation

The Maglev system considered for the California Line could be subjected to 40 MW power fluctuations, from 10 to 50 MW, every 30 seconds or twice per minute during maximum traffic conditions of 12,000 passengers an hour. To meet the above Criteria, as shown by Figure 6, for this frequency, the Voltage Flicker should be less than 1.5 percent.

The resulting percent Voltage Flicker can be estimated by using the following formula :

$$VOLTAGE\ FLICKER\ (\%) = 100 \times (IR \cos\varphi + IX \sin\varphi)$$

With :

MVA Base 100 *MVA*

$$I\ (\ p.u.\ ) = \frac{MVA\ Power\ Fluctuation}{MVA\ Base} = \frac{MVA\ Power\ Fluctuation}{100}$$

$$\cos\varphi = Load\ Power\ Factor = PF$$

$$\sin\varphi = \sqrt{1 - PF^2}$$

Z = *System Short Circuit Impedance in p.u.*

$$Z = \frac{MVA\ Base}{MVA\ System\ Short\ Circuit\ Duty} = \frac{100}{MVA\ System\ Short\ Circuit\ Duty}$$

R = *System Short Circuit Equivalent Resistance* = $Z \cos\delta$

X = *System Short Circuit Equivalent Reactance* = $Z \sin\delta$

δ = *System Short Circuit Equivalent Impedance Angle*

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It can be seen that the voltage flicker depends on the power factor of the Maglev Substation load and the angle of the System short circuit equivalent impedance at the point of connection.

A study was conducted to demonstrate the sensitivity of the voltage flicker at each connection point to the power factor of the Maglev Substation load, by considering the values of 1.0, 0.95, 0.90, and 0.85.

It was found that, at unity power factor the voltage flicker is minimum, in fact it is 0 when the System Short circuit equivalent Impedance has a 90 degree angle, which is the case at most point of connections located at the subtransmission side of the "Source" Transmission Substations. This is caused by the preponderance of the transformer impedance (11 percent on 150-MVA base) which has a high X/R ratio, typically more than 65 for transformers of this size (150 MVA).

It was also found that, if the power factor of the Maglev Substation load is less than unity, several Maglev Substations, which can be served at a Subtransmission voltage at unity power factor, would have to be served at 230 kV, because the voltage flicker would exceed 1.5 percent.

For instance, if the load power factor is 0.95, this would be the case for six Maglev Substations in the PG&E service territory, Substations 17, 18, 19, 38, 39, and 40, which would result in an additional cost of $71.5 M.

These findings, in addition to the need for adequate voltage support, show the importance of maintaining unity power factor at all Maglev Substations.

CONCLUSIONS

The total Cost estimates (1992 level) for the Electric Utility Power System requirements for the California Maglev Line are respectively $1.62 and $1.76 Billion, or an average of $2.7 and $2.8 M per mile of Maglev Line, for each Alternative: Altamont Pass and Pacheco Pass.

About 53.5 percent of these Total Costs are for the new Maglev Substations, 13.5 percent for additions at existing Substations, and 33.0 percent for Transmission and Subtransmission line work.

The cost of land associated with these facilities is respectively 12.4 and 15.9 percent of the Total Costs.

These large costs result from the magnitude of the project : respectively 590 and 628 miles of Maglev line, 52 and 55 Maglev Substations, and hundreds of miles of new or rebuilt Transmission and subtransmission lines, ranging from about 100 miles at 66 kV, 500 miles at 115 kV, to 340 miles at 230 kV.

These costs may be reduced by optimizing the system design, such as increasing the distance between the Maglev substations, or accepting the loss of one Maglev substation, which may result in higher costs for the transmission and subtransmission lines and the 12-kV DC cables along the Maglev line. Optimization will aslo be possible, during the next phase of the study, when detailed simulations of the Maglev system loads are available.

Together with the 12-kV DC cables and the inverters along the Maglev line, the power system requirements were found to have the second largest cost with $5.6 M per mile of Maglev line, out of a total of $23 M , after the guideway system ($9.1 M), as subsequently indicated in the Final Report of the National Initiative Bechtel Team (Reference 8).

To avoid even higher costs, the study indicated that unity power factor should be maintained and harmonics should be within criteria limits, for all Maglev Substation loads.

REFERENCES

1. Center for Continuous Study of the California Economy, California Population Characteristics, Report, Special Edition April 1990.

2. Southern California Edison Company, Transmission Planning Criteria and Guidelines, (Approved by the Plant Expenditure Review Committee in November 14, 1989).

3. Roy Billinton and Ronald Allan : Reliability Evaluation of Engineering Systems. Plenum Press, New York and London, 1983.

4. P. Save de Beaurecueil : Southern California Edison Company, Transmission Line Outages Statistical Analysis, 1980 Reliability Conference for the Electric Power Industry, Proceedings, Pages 27-38.

5. EDF Regional Systems Planning Guide - Systems Structures and Operation, Section 26, Article 262, Harmonics, dated 1/1/90.

6. Barnes, R. Wong, K. T : Unbalance and Harmonic Studies for the Channel Tunnel Railway System, IEE Proceedings Paper, Part B Electric Power Applications v 138 n 2 March 1991, p 41-50.

7. V. Sabate : Electric Disturbances generated by Electric Train Locomotives, Revue Technique GEC Alsthom No. 5 1991. (Paper describes harmonics filtering used for TGV systems)

8. National Maglev Initiative Bechtel Team, Maglev System Concept Definition Final Report, Prepared for the U.S. Department of Energy and the Federal Railroad Administration under Contract DTFR 53-92-C-00003, Dated September 30, 1992.
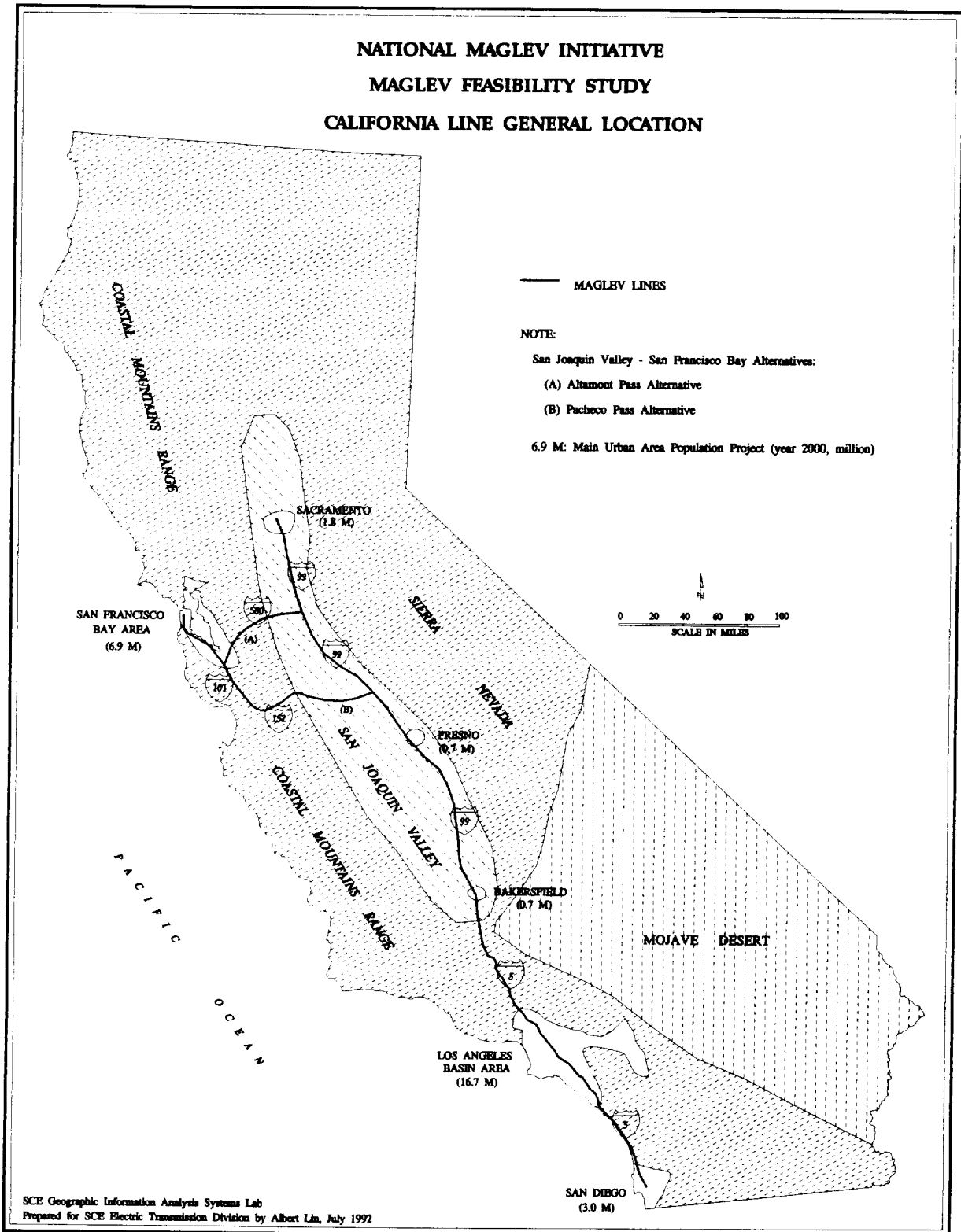
Figure 1. Maglev California line general location.

NATIONAL MAGLEV INITIATIVE
MAGLEV FEASIBILITY STUDY - CALIFORNIA LINE
MAGLEV SUBSTATIONS & UTILITY POWER SYSTEM (500 & 230KV)
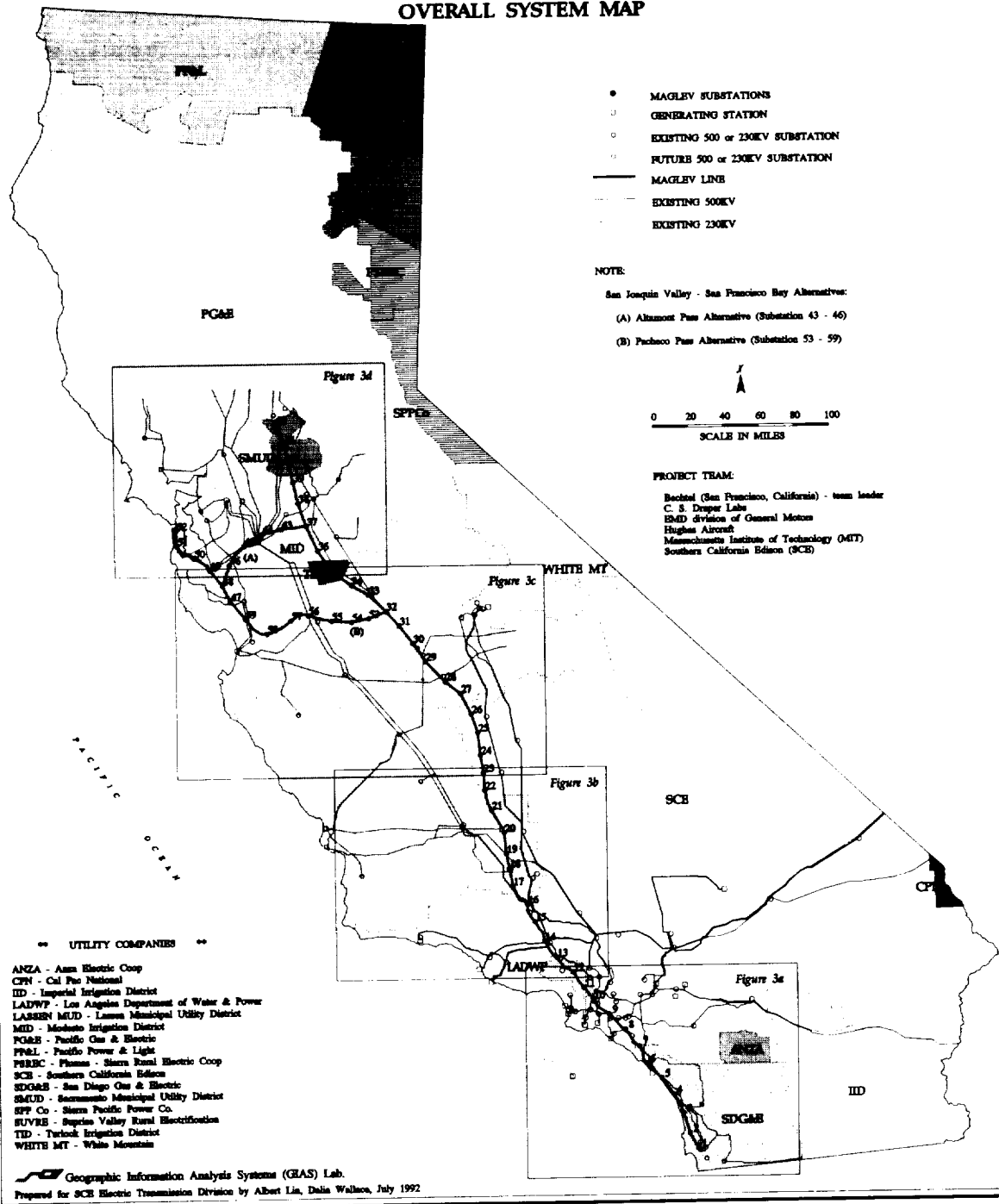#### OVERALL SYSTEM MAP

•   MAGLEV SUBSTATIONS

    GENERATING STATION

○   EXISTING 500 or 230KV SUBSTATION

    FUTURE 500 or 230KV SUBSTATION

——— MAGLEV LINE

---- EXISTING 500KV

···· EXISTING 230KV

NOTE:

San Joaquin Valley - San Francisco Bay Alternatives:

(A) Altamont Pass Alternative (Substation 43 - 46)

(B) Pacheco Pass Alternative (Substation 53 - 59)

0   20   40   60   80   100
SCALE IN MILES

PROJECT TEAM:

Bechtel (San Francisco, California) - team leader
C. S. Draper Labs
EMD division of General Motors
Hughes Aircraft
Massachusetts Institute of Technology (MIT)
Southern California Edison (SCE)

** UTILITY COMPANIES **

ANZA - Anza Electric Coop
CPN - Cal Pac National
IID - Imperial Irrigation District
LADWP - Los Angeles Department of Water & Power
LASSEN MUD - Lassen Municipal Utility District
MID - Modesto Irrigation District
PG&E - Pacific Gas & Electric
PP&L - Pacific Power & Light
PSREC - Plumas - Sierra Rural Electric Coop
SCE - Southern California Edison
SDG&E - San Diego Gas & Electric
SMUD - Sacramento Municipal Utility District
SPP Co - Sierra Pacific Power Co.
SUVRE - Surprise Valley Rural Electrification
TID - Turlock Irrigation District
WHITE MT - White Mountain

Geographic Information Analysis Systems (GIAS) Lab.
Prepared for SCE Electric Transmission Division by Albert Lie, Dalia Wallace, July 1992

Figure 2. Maglev California line overall system map.

Figure 3. Maglev California line system map, Bakersfield-San Francisco section.
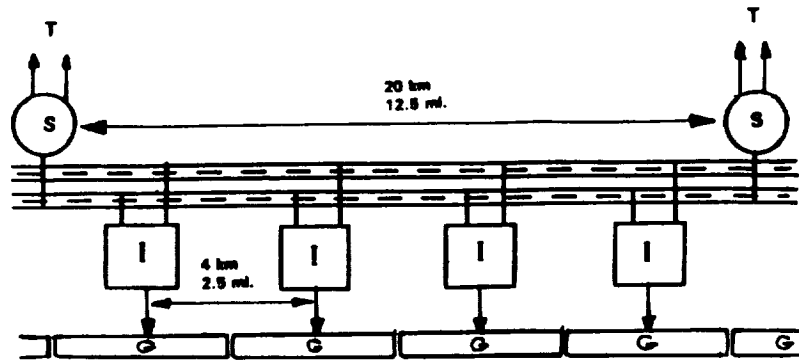
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Figure 4. Maglev power supply system configuration between two consecutives maglev substations.
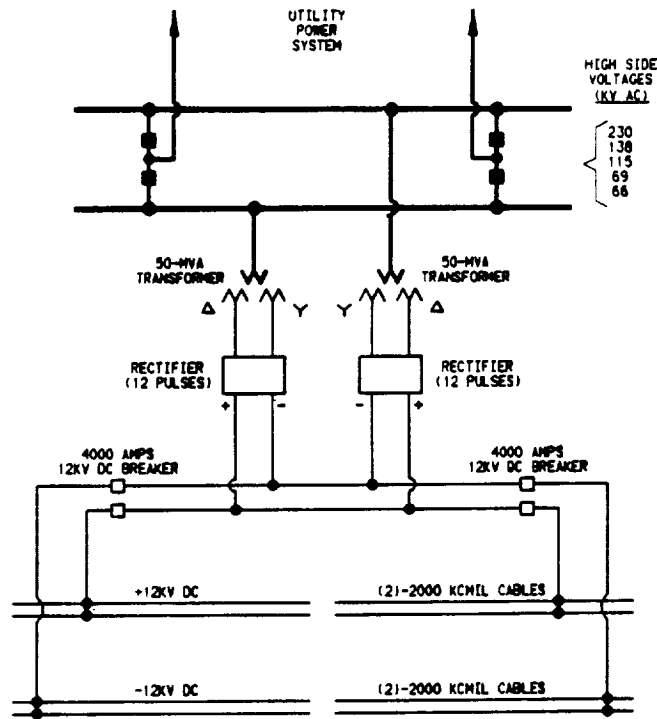

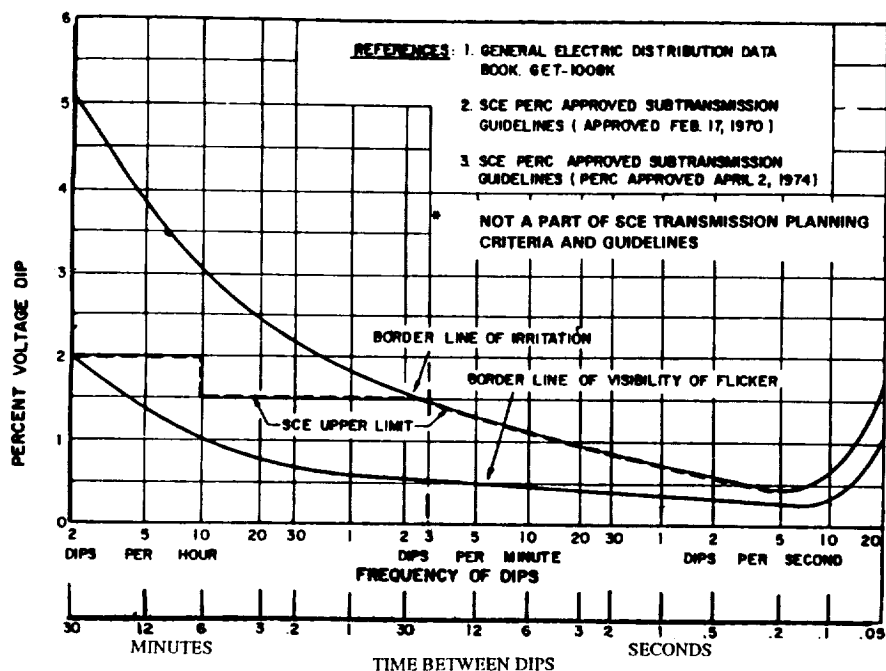Figure 5. Maglev substation schematic one line diagram.

Figure 6. Southern California Edison Company
Voltage fluctuation design limits.

Table 1. Limit harmonics rates, from EDF planning guide, not part of SCE transmission planning criteria.

LIMIT HARMONICS RATES WHICH CAN BE CREATED ON SYSTEM BY ALL CUSTOMERS SERVED AT A GIVEN VOLTAGE LEVEL								
Odd Harmonics Non Multiples of 3			Odd Harmonics Multiples of 3			Even Harmonics		
Rank	Harmonics Voltage (Percent)		Rank	Harmonics Voltage (Percent)		Rank	Harmonics Voltage (Percent)	
n	Distrib.	Subtrans. & Trans.	n	Distrib.	Subtrans. & Trans.	n	Distrib.	Subtran & Trans
5	4.6	2	3	3.8	2	2	1.3	2.1
7	3.8	2	9	1.1	1	4	1	1.4
11	2.7	1.5	15	0.2	0.3	6	0.5	0.7
13	2.3	1.5	>21	0.2	0.2	8	0.2	0.3
17	1.5	1				10	0.2	0.3
19	1.2	1				>12	0.2	0.3
23	1.2	0.7						
25	1.2	0.7						
>25	0.15 + 10 / n	0.1 + 2.5 / n						

NOTES :
1. Harmonics Voltage (Percent) = (Harmonics Voltage of rank n) / (Normal Positive Sequence Voltage)

2. Distrib. = Distribution Voltage Levels (33, 16, 12, and 4 kV)

3. Subtrans. = Subtransmission Voltage Levels (138, 115, and 66 kV)

4. Trans. = Transmission Voltage Levels (500 and 230 kV)

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Session 6a – Controls

Chairman: Roland Siegwart
MECOS Traxler