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A SURVEY OF RAILROAD AC ELECTRIFICATION SYSTEMS THROUGHOUT THE WORLD

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16. Abstract

This report describes the major features of various railroad electrification schemes for supplying the catenary from the source of power for ac operation. These features include: details of the power source, high-voltage substation connections, substation details, catenary-to-substation connections, track sectioning methods, and any other special electrification features.

The ten countries surveyed for this report are: United States, United Kingdom, France, U.S.S.R., Japan, Federal Republic of Germany (W. Germany), Sweden, Switzerland, Taiwan, and South Africa.

This report is a compilation of available literature and is not an assessment or analysis of any electrified railroad system.

The basic electrification parameters, as well as the similarities between systems are presented in the conclusions. Further work using this report as a basis is suggested in the recommendations.

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PREFACE

<u>A Survey of Railroad AC Electrification Systems Throughout the World</u> provides a summary of the basic parameters and operational features of the various schemes in use to feed the electric power to the catenaries from the wayside and utility power sources. The available types of electric power, substation and track sectioning details are also discussed for the ten countries surveyed. Critical evaluation of these systems is considered as beyond the scope of this task.

This work was performed under the direction of Frank L. Raposa of TSC under Contract DOT/TSC-1452, Task No. 3. Dr. Alexander Kusko, Jeffrey J. LaMarca, and Charles M. King are all employed by Alexander Kusko, Inc.

EXECUTIVE SUMMARY

The Federal Railroad Administration (FRA) anticipates the conversion of railroads in the United States to electrified operation as the result of continuing difficulties over oil supplies and cost. Electrification of U.S. railroads could begin immediately by adapting existing technology from abroad. However, the magnitude and longevity of the capital investment makes it desirable to thoroughly evaluate the technology appropriate for the U.S. application from the numerous ac design schemes that have been installed elsewhere.

The objective of this report is to describe the major features of these schemes, including details of power sources, substations and track sectioning. Ten countries are included in this study: the United States, the United Kingdom, France, the Soviet Union, Japan, the Federal Republic of Germany (W. Germany), Sweden, Switzerland, Taiwan and South Africa. The system descriptions in this report are based on information currently available in the literature. This report is not intended to be an assessment of the railroad electrification systems; it is intended to be an orderly compilation of available information.

A summary of the basic parameters of the electrification systems in the ten countries is shown in Table A.

System Types

Two types of electrification systems exist; the dedicated system and the utility-dependent system:

Table A

Basic Parameters of Railroad Electrification Systems in the Countries Surveyed

Country	Electrified AC Route - KM (1977)	Catenary Voltage & Frequency	Transmission Voltage (kV)	Substation Spacing (KM)
United States	720	11 kV - 25 Hz	132	16
		25 & 50 kV - 60 Hz	138, 230	**
United Kingdom	1500	25/6.25 kV-50 Hz	132	25-30
France	4500	25 kV - 50 Hz	63, 90, 220	41-67
U.S.S.R.	14900	25 kV - 50 Hz	110	45-50
Japan	4200	20 &25 kV - 50 &60 Hz	220, 270	30-50
W. Germany	9930	15 kV - 16 2/3 Hz	110	60-80
Sweden	7400	15 kV - 16 2/3 Hz	6	*
Switzerland	3500	15 kV - 16 2/3 Hz	66, 132	25-30
Taiwan	540	25 kV - 60 Hz	69	40-50
South Africa	1045	25 &50 kV - 50 Hz	88, 132	30 &140

*No information available

**Only one substation exists in presently operating systems

The dedicated system operates with a nonstandard power frequency (16 2/3 or 25 Hz).

The utility-dependent railroad system operates at the power frequency of the local utility (50 or 60 Hz).

Table B below categorizes the systems for the countries studied:

Table B

Types of Electrification Systems Used

Dedicated System (16 2/3 or 25 Hz)	Utility-Dependent System (50 or 60 Hz)
Federal Republic of Germany	United Kingdom
Sweden	France
Switzerland	U. S. S. R.
United States	Japan
• Penn Central (former)	Taiwan
• Reading (former)	South Africa
	United States
	• Muskingum
	• Black Mesa & Lake Powell
	• Texas Utilities
	• New Haven (New)
	• Erie Lackawanna (New)
	• Northeast Corridor (New)
	• FRA Test Track

Feeding the Catenary

Three different methods of feeding the catenary from a utility network are the center-feed, the single-end-feed and the double-end-feed methods. Table C categorizes those countries using utility-generated power into these groupings:

Table C

Methods of Feeding the Catenary from the Utility Network

Center-Feed	Single-End-Feed	Double-End-Feed
United Kingdom	United States • Erie Lackawanna (60 Hz) • New Haven* (60 Hz)	France
South Africa		U.S.S.R.
United States • New Haven* (60 Hz)		Japan
		Taiwan

*One substation in their system uses the single-end-feed system while the other two substations use the center-feed system.

Substations

Substations which supply the railroad vary in their degree of redundancy. Table D which follows lists the countries studied as having either complete redundancy or partial redundancy of power supply to the catenary.

Table D

Degree of Substation Internal Redundancy

Complete Redundancy	Partial Redundancy
United Kingdom*	United Kingdom*
France	Sweden
Japan	South Africa
W. Germany	United States
Switzerland	• Muskingum
Taiwan	• BM & LP
United States (11 kV-25 Hz)	• New Haven (60 Hz)

*Substation required to supply higher loads and those located at branches in the railroad system are completely redundant while other substations are only partially redundant.

Phase Shift at Phase Breaks

The railroad which are supplied directly from the utility power network have either a 120° phase shift or 90° phase shift across each phase break. Table E shows where each of these phase shifts is in use:

Table E

Degrees of Phase Shift at Phase Breaks

120° Phase Shift	90° Phase Shift
United Kingdom	Japan
France	Taiwan
U.S.S.R.	United States
South Africa	• New Haven (60 Hz)*
United States	
• Erie Lackawanna (60 Hz)	
• New Haven (60 Hz) *	
• Northeast Corridor (60 Hz)	

*The phase break at Cos Cob has a 90° phase shift while the other two phase breaks have a 120° phase shift.

Booster Transformers

Booster transformers are used by some countries to reduce electromagnetic interference (EMI) to communications equipment caused by earth return currents. The countries which use booster transformers are listed in Table F.

Table F

Booster Transformers

United Kingdom
U.S.S.R.
Japan
Sweden
South Africa

Autotransformers

Autotransformers are used by some countries to allow substations to be spaced further apart while still obtaining the EMI reductions of the booster transformer. The countries which use autotransformers are listed in Table G.

Table G

Autotransformers

France
Japan
U.S.S.R.*
United States
- New Haven (25 Hz)
- New Haven (60 Hz)
- Erie Lackawanna (60 Hz)

*Planned future use.

Voltage-Regulated Transformers

Voltage-regulated transformers are used on systems where substations are connected to adjacent substations through the catenary (double-end-feed). The countries which use voltage-regulated transformers are listed in Table H.

Table H

Voltage-Regulated Transformers
France
Switzerland

Recommendations

It is recommended that further work be done using this survey as the basis to evaluate systems for use in North America. This should be accomplished by: first, conducting an analysis of the systems used in the United Kingdom, France and Japan to evaluate the use of each system in its respective country; and second, conducting an evaluation of selected systems with regard to operations on North American railroads.

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1.0 INTRODUCTION

1.1 Scope of Report

Various schemes for supplying the catenary from the source of power have been employed by railroads which have been electrified for ac power operation. This report describes the major features of these schemes. These features include, the details of the power source; the high-voltage substation connections; the substations; the catenary connections from substations; the track sectioning methods and the features of any other major electrification equipment.

Ten countries were surveyed because they include examples of all the major ac electrification systems in worldwide use. The countries included in this study are: United States, United Kingdom, France, U.S.S.R., Japan, The Federal Republic of Germany (W. Germany), Sweden, Switzerland, Taiwan, and South Africa.

The electrification system descriptions in this report are based on information currently available in the literature. Excerpts from the literature are used throughout this report where necessary to describe parts of the systems. This report is not intended to be an assessment or analysis of railroad electrification systems used throughout the world. Rather, it is intended to be an orderly compilation of available information in the current literature on these systems.

1.2 Typical Configurations

This section illustrates the physical sizes, spatial relationships and terminology of the various components used in typical railroad electrification systems. Figs. 1.1 and 1.2 provide a view of a substation and a section of catenary used on the 25 Hz Penn Central line. Figs. 1.3 and 1.4 show a section of catenary and a booster transformer arrangement used on the Swedish Railways.

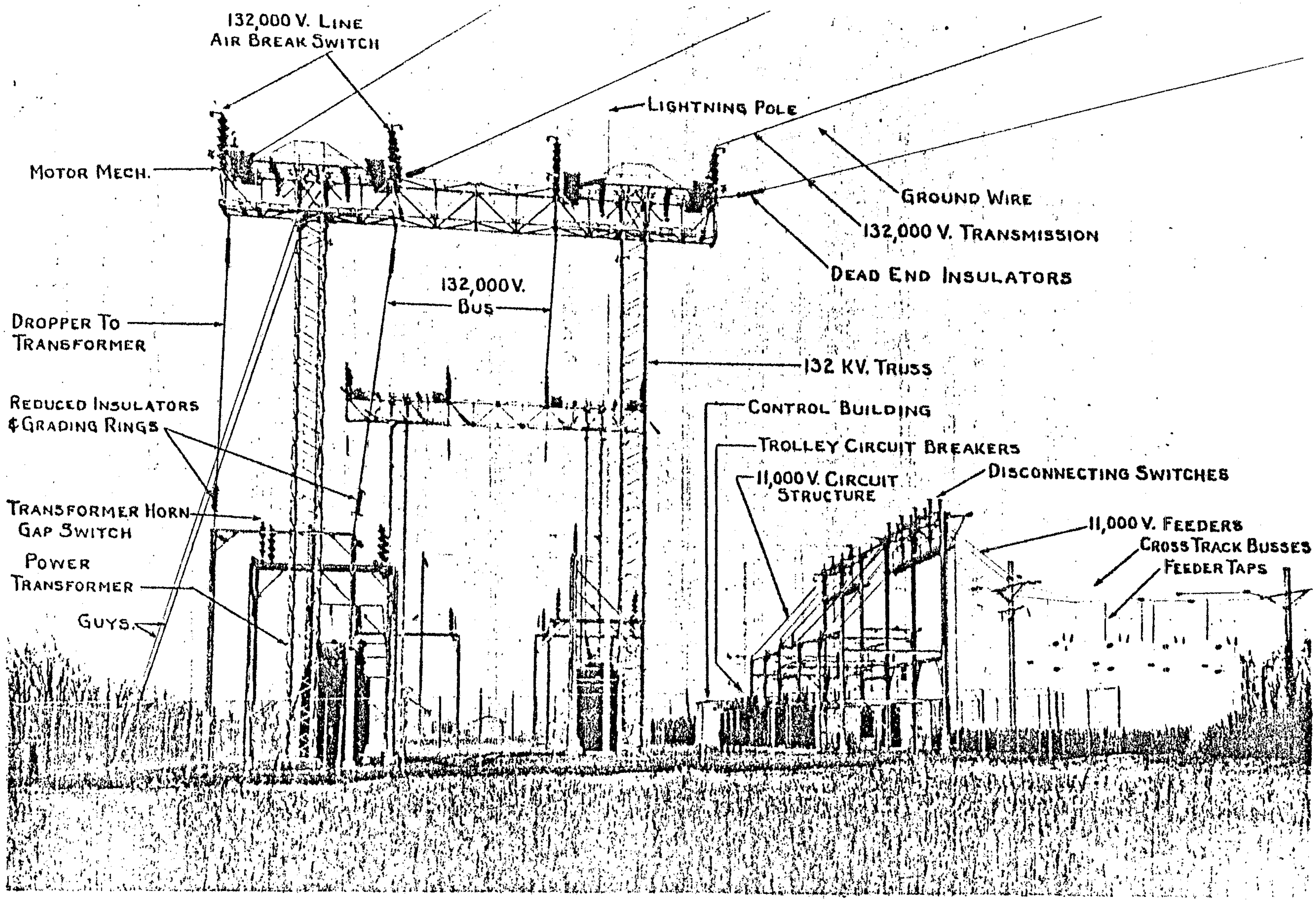


Fig. 1.1 Typical Physical Arrangement of a Penn Central 25 Hz Substation

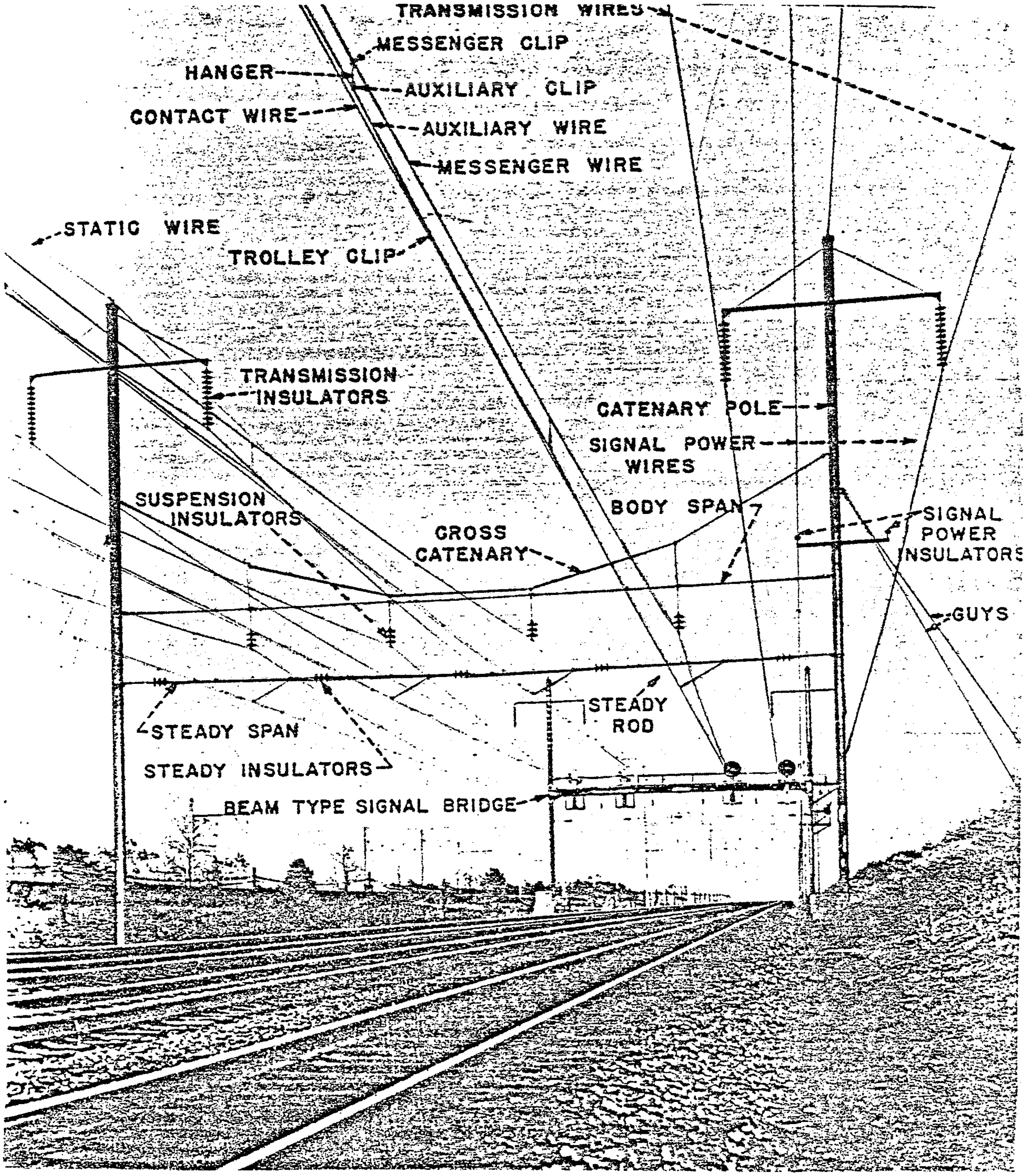


Fig. 1.2 Typical Physical Arrangement of a Penn Central 25 Hz Catenary Section

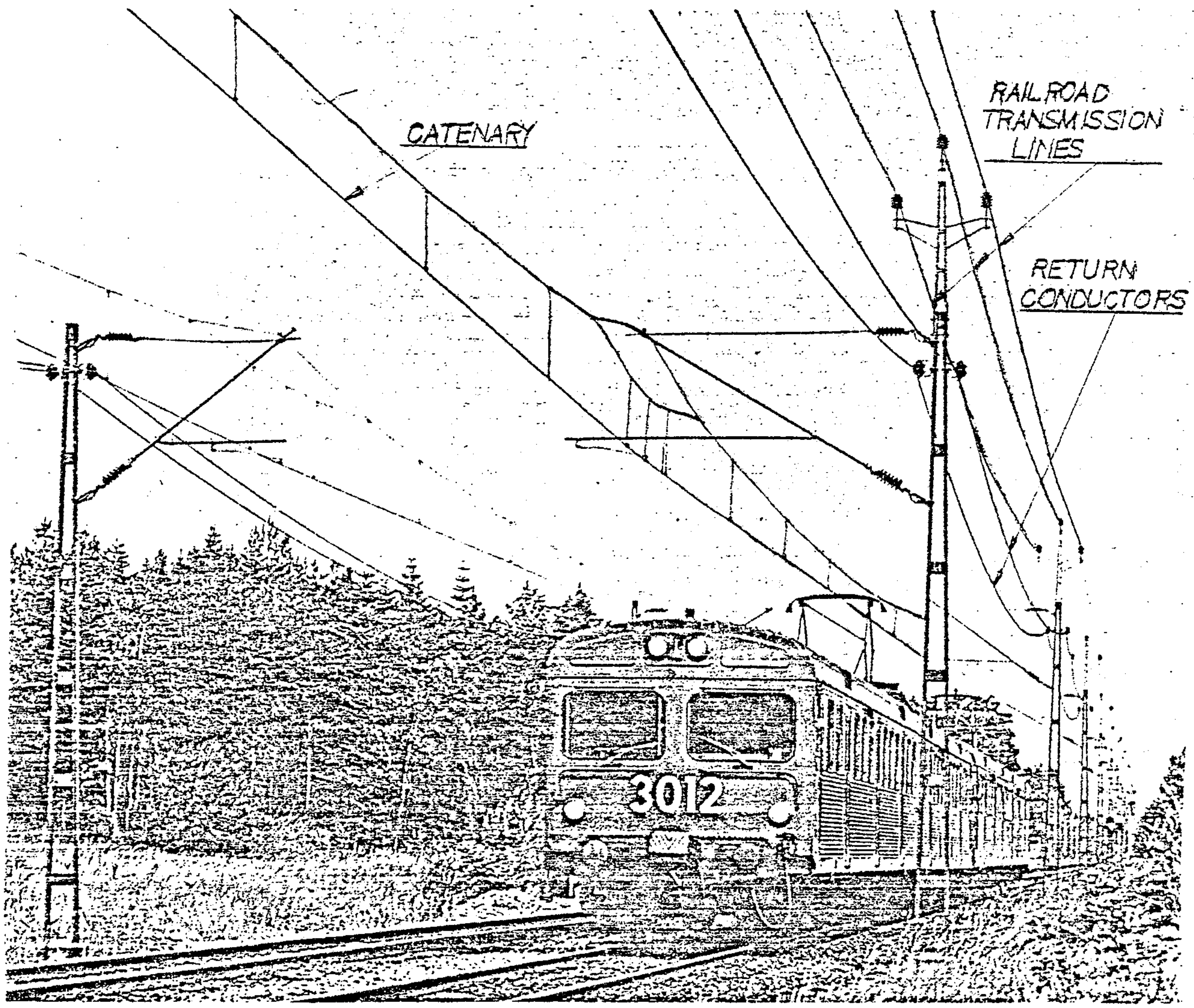


Fig. 1.3 Typical Physical Arrangement of a Swedish Railways' Catenary Section

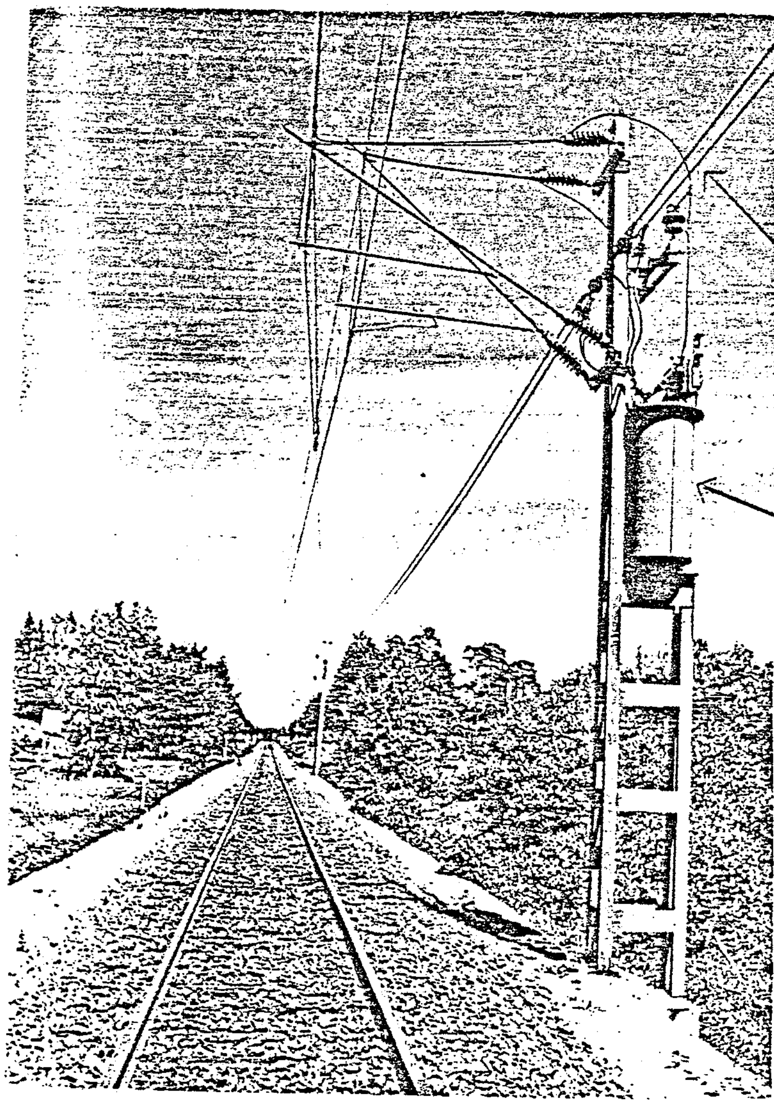


Fig. 1.4 Typical Physical Arrangement of a Swedish Railways' Booster Transformer

1.3 Glossary of Definitions

The following terms and phrases that appear in this report were taken from the referenced sources and may require further explanation or definition as provided below:

Banked transformers (UK) -The interconnection of transformers on the primary winding at a substation which allows the railroad transformers to be located at the same substation as the utility's transmission/ distribution transformers.

Catenary - A term describing the overhead conductor, contacted by the pantograph or trolley current collecting device, and its support structure.

Center Feed - Method of supplying the catenary where power is supplied at the midpoint of the catenary section at one phase and is separated from the adjacent substations by phase breaks.

C. E. G. B. - Central Electricity Generating Board which operates the utility system in England.

Ceramic bead insulators (UK) - Non-conducting material that is used as the part of a phase break that makes contact with the pantograph.

Double-End-Feed - Method of supplying one section of catenary from both ends with the same phase by the two adjacent substations.

Feeder (UK) - Cable which connects the railroad substation with the catenary.

Feeder Breaker - Circuit breaker which interrupts the flow of current in a feeder in the event of a fault.

Feeder station (UK) - Railroad substation which supplies power to the catenary.

Feeding section (UK) - The section of catenary which is supplied by one feeder station (railroad substation).

Frequency changer - A rotary electrical device or a static device which is used to change the utility frequency power to the dedicated railroad frequency.

Grid substation - A substation of the National Grid or public utility in UK.

National Grid - The name given to the high voltage transmission network in the UK.

Neutral section (Earthed or Floating) (UK) - The section of catenary that is not energized and can act as a phase break.

Overhead Line - A portion of overhead catenary wire used to supply power to all electric locomotives or EMU cars on the track below that wire.

Pantograph - Mechanism atop electric locomotive used to contact the catenary wire and conduct power to locomotive from the wire.

Phase break - The section of catenary where special equipment exists to separate the voltage being supplied at different phases by the two adjacent supply substations.

Ring - Busbar Stations - A utility substation with three or more interconnected transformers.

Scott-connected transformer - A special transformer arrangement that converts three-phase power to two-phase power and results in a balanced three-phase load when the two-phase loads are equal.

Single-End-Feed - Method of supplying the catenary where power is supplied at one phase in one direction from the substation and is separated from the adjacent substation by a phase break.

Step-down Substations - A substation that contains transformers which reduce the utility supply voltage (usually 115 kV or greater) to the catenary voltage.

Sub-Feeder Station (UK) - A railroad supply substation that obtains its power directly from the utility distribution system. (Used in the London, England area at 6.25 kV).

Transformer Feeder (UK) - Cable which connects the utility system to the railroad supply transformer.

Track Feeder - See Feeder

Track sectioning cabin (UK) - Enclosures located midway between railroad supply substations that contain the switching and protection equipment for the sections of catenary on both sides of the neutral section.

Track sectioning - Process and equipment available to isolate a section of catenary from another catenary section or from the supply substation.

Wood-bridge-connected transformer (Japan) - A special transformer arrangement that performs the same function as a Scott-connected transformer and also permits the grounding of the wye-connected primary winding.

1.4 Legend of Symbols

The electrical schematic figures included in this report originated in various native and foreign references (as listed at the end of each section). Therefore, there was no uniform code of symbols used to represent the various electrical components, such as transformers, circuit breakers, etc.

A summary of the major symbols used in the figures in this report is illustrated in Fig. 1.5. Other symbols peculiar to a particular figure, and not appearing elsewhere, are explained in the caption attached to that figure.

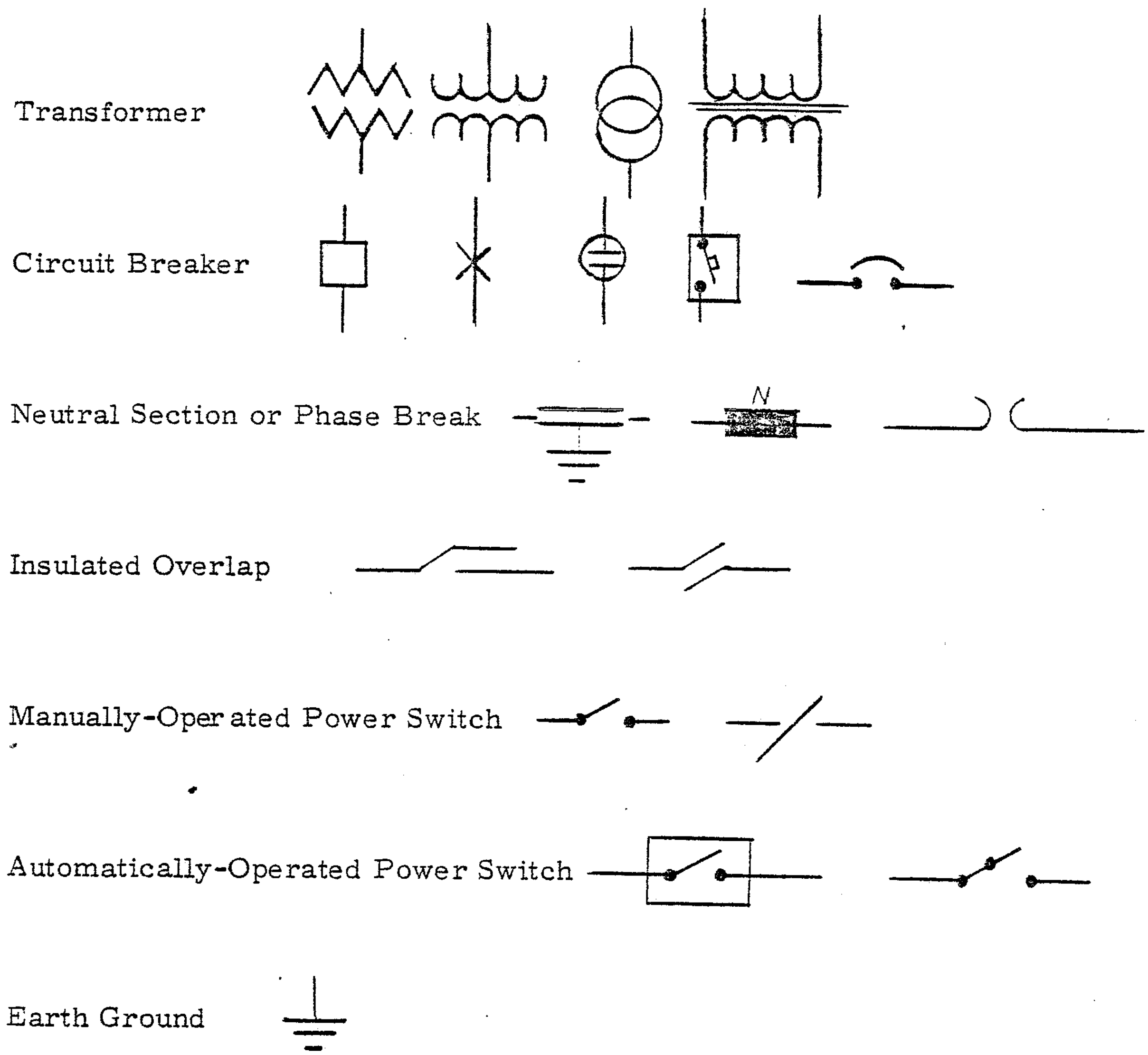


Fig. 1.5 Legend of Symbols Used in the Figures of This Report

2.0 UNITED STATES OF AMERICA

The American electrified railroad dates back to 1888, when F. Sprague put the first successful trolley line in operation in Richmond, VA. Overhead dc lines were used to distribute the power.

In 1915 an ac system was placed in operation on the (then) Pennsylvania Railroad. Alternating current at 11 kV and 25 Hz was selected to avoid ac-to-dc converter stations and to take advantage of the smaller conductor size and greater substation spacing resulting from the higher trolley voltage. A frequency of 25 Hz was chosen rather than 60 Hz since it was necessary to use series-wound ac traction motors, and the commutation problem at 60 Hz was insurmountable, but could be solved at 25 Hz.[2.1]

Recently, the Muskingum Electric Railroad introduced the widely deployed 25 kV commercial frequency electrified railroad to the United States; this design has gained wide acceptance in other countries. Another first is the 50 kV 60 Hz system installed for the Black Mesa & Lake Powell Railroad. Further description of these and other systems follows.

Due to the lack of a design standard for railroad electrification, no uniformity exists for the various dedicated and utility-fed lines that have been built and used in the United States. The dedicated lines (11 kV 25 Hz) include the former Penn Central line, the former Reading line, and the former New York, New Haven and Hartford line. The utility-fed lines (60 Hz) include the newly-converted (operational in 1981) 12 kV New Haven Line, the 25 kV Muskingum

Railroad, the 25 kV Texas Utilities Line, the 13/26/52 kV FRA Test Track (Pueblo), the 25 kV newly-converted Erie Lackawanna Line, the 25 kV newly-converted Northeast Corridor, and the 50 kV Black Mesa & Lake Powell Railroad. Each of the three dedicated and seven utility-fed U.S. railroad lines listed above is addressed in a separate subsection. Each of the other nine countries included in this report has more or less standardized its electrification system, so separate subsections for their various railroad lines are not required.

The United States has a total of 2328 route km electrified, as shown in Table 2-1.

2.1 Penn Central Railroad (Former) 11 kV 25 Hz

Presently, electrification in the Northeast uses the 11 kV 25 Hz dedicated system. The trackage is composed of the former Penn Central and Reading Lines, which are now part of the Amtrack/ Conrail system. A map provided in Fig. 2.1 shows a portion of the system, including the location of the electrical facilities (see legend). Approximately 1220 route-km exists on the former Penn Central Line while the Reading Line has a total of 141 route-km.

2.1.1 Source of Electric Power

All power for the railroad is purchased at 13,200 volts, 25 Hz single-phase from four electric power companies along the right-of-way. This power is generated at seven utility-owned locations, using seventeen generators and frequency changers. It is then stepped up to 132,000 volts single-phase at six supply point substations, and transmitted over railroad-owned power lines (Fig. 2.2) to

Table 2-1

Extent of AC Electrification in the United States as of 1973 (Ref. 2.2)

Country, Railway, and Lines Electrified	Length Electrified		Voltage	System of Electrification	Conductor	Year Electrified
	Route Km.	Track Km.				
United States—						
Amtrak	1,334	4,356	666	D.C.	3 R	1907
			650	D.C.	3 R	
			11,000	1/25	O H	1907-37
			650	D.C.	3 R	
Con Rail	441	1,185	3,000	D.C.	O H	1925
			11,000	1/25	O H	1928
			650	D.C.	3 R	1915
Long Island	214	536	700	D.C.	3 R	1905-26 and 1970
Reading	146	309	11,000	1/25	O H	1906-38
Illinois Central Gulf	62	210	1,500	D.C.	O H	1926-29
Richmond, Fredricksburg & Potomac	5	43	..	..	..	..
Black Mesa and Lake Powell	126	134	50,000	1/60	O H	1973
Total	2,328	6,773	..	..	..	..

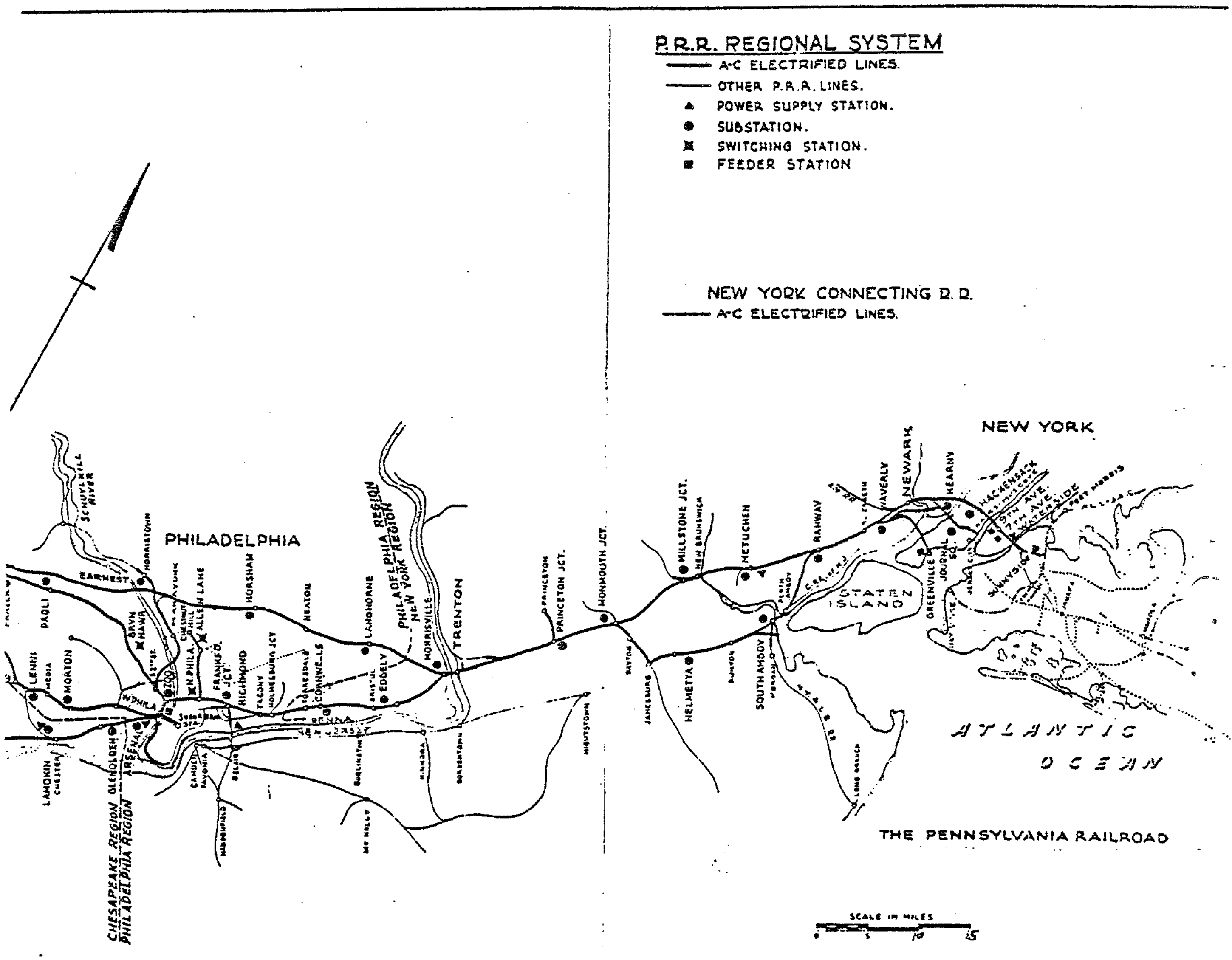
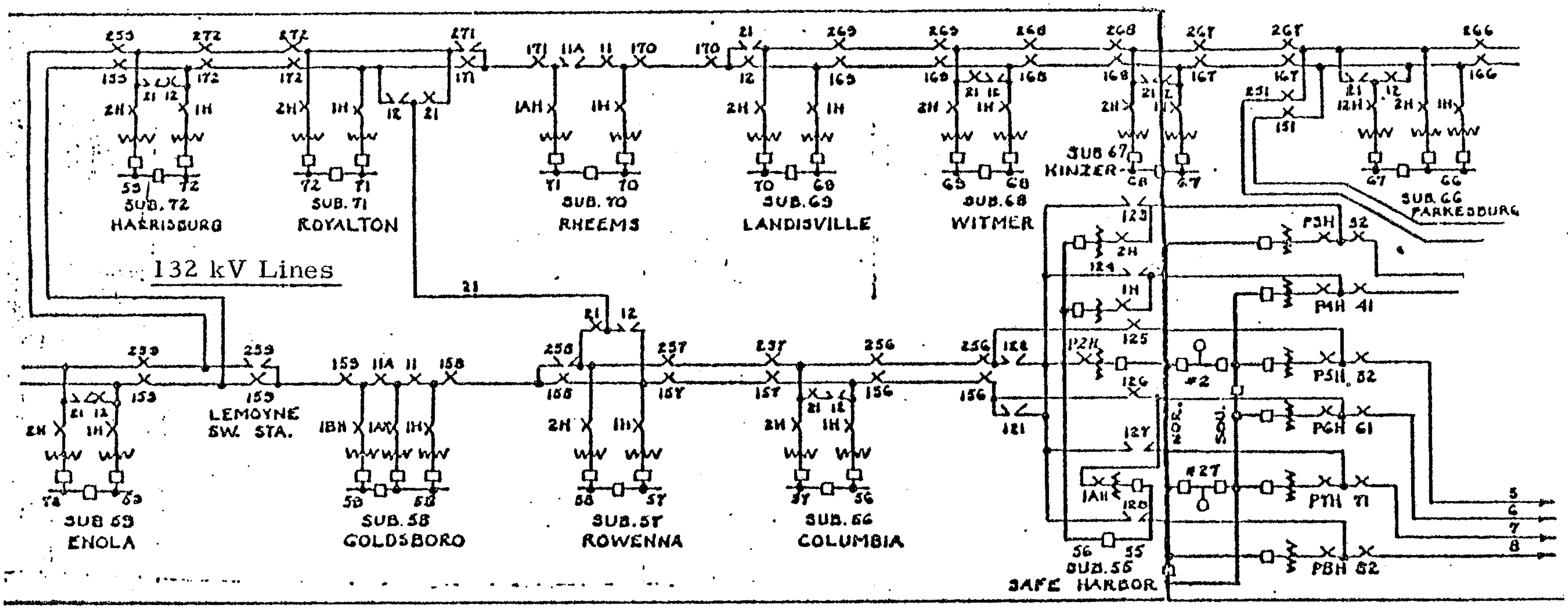


Fig. 2.1 Map of a Portion of the Former Pennsylvania Railroad Electrified Territory (Ref. 2.3)



—X— Air Break Switch Normally Closed

⋋ ∠ Air Break Switch Normally Open

Fig. 2.2 Electrical Schematic Diagram of a Portion of 132 kV Transmission Line Network - Former Penn Central Railroad (Ref. 2.4) stepdown-substations (Fig. 2.3), where it is reduced to approximately 12,500 volts for connections to the catenary or trolley wires.[2.3]

2.1.2 Method of Supplying Catenary

The 11,000 volt catenary system is energized from the railroad-owned substations, which contain the apparatus to control power taken from the 132,000-volt transmission system. A typical substation is depicted in Fig. 2.3. Sixty-seven substations and switching stations supply power to the overhead contact wire system. Substations are spaced as close as 4 km apart where commuter traffic and heavy mainline traffic merge; an average spacing of 16 km is used between the cities.[2.3]

2.1.3 Track Sectioning

Track sectioning equipment is provided so that a section of catenary can be electrically isolated for maintenance purposes.

2.2 The New York, New Haven and Hartford Railroad (Former) and the Reading Railroad (Former) - 11 kV 25 Hz

Autotransformers were first introduced on the New York, New Haven & Hartford Railroad in 1913, where this so-called three-wire feeding arrangement is still in use. This arrangement was also used by the Reading Railroad, but never achieved general popularity or use on other lines, because the low-frequency ac traction systems favored up to the 1950s did not necessarily require booster transformers and return conductors for reduction of electromagnetic interference (EMI) caused by earth currents that could degrade performance of communications and signalling circuits.[2.5]

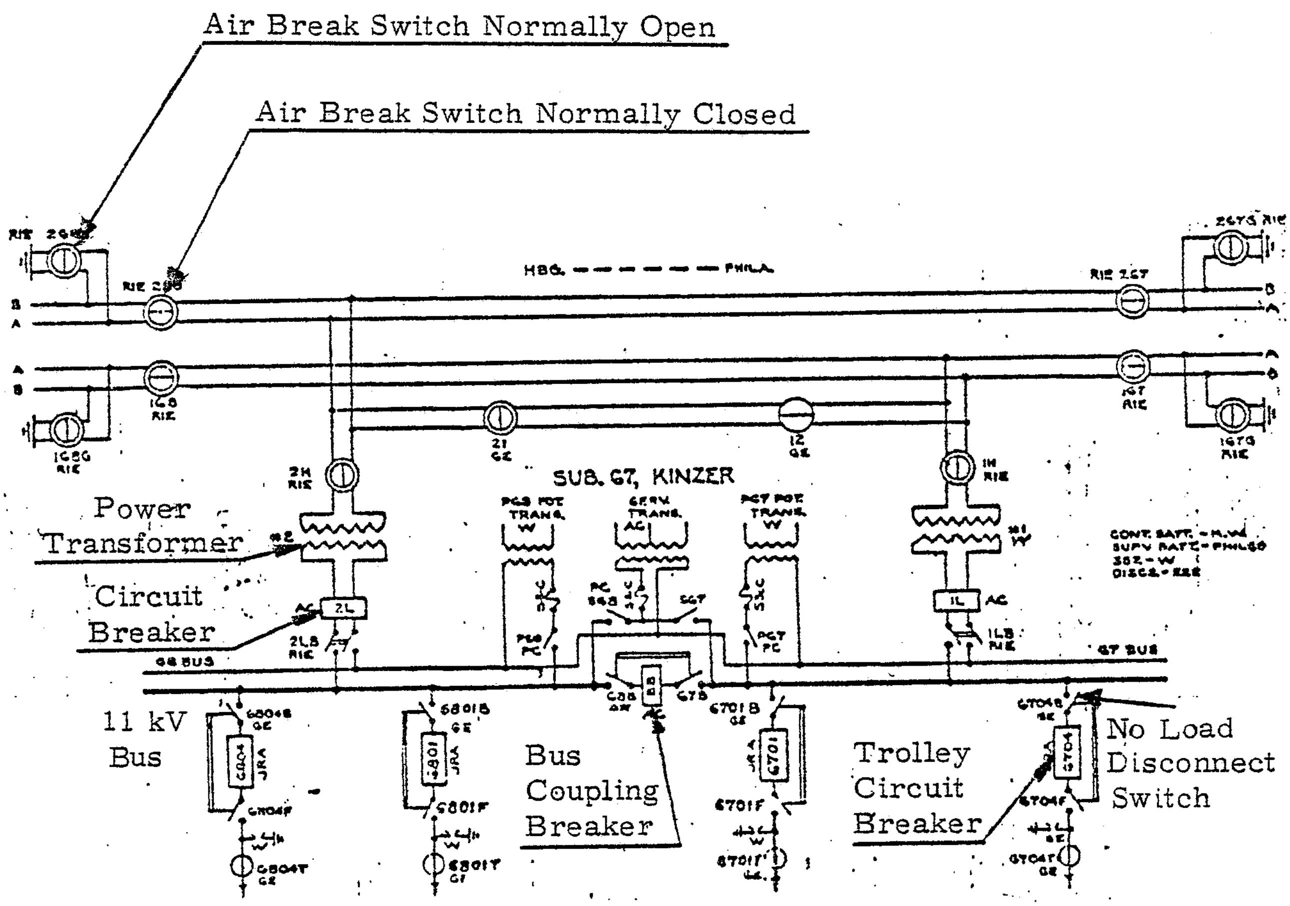


Fig. 2.3 Electrical Schematic Diagram of a Typical Substation Used on the Penn Central Railroad (Ref. 2.4)

[Note the 132 kV transmission line taps and equipment on 11 kV 25 Hz bus]

2.2.1 Source of Electric Power

The electrification on the New York, New Haven & Hartford Railroad (NY, NH & H) uses 3-phase, 11 kV 25 Hz power from special generating stations. Two phases are tapped to energize the trolley and feeder wires of the autotransformer system, while all three phases are installed along the wayside on masts to provide power for substations, station lighting and control (Fig. 2.4). About 200 route km exist on the NY, NH & H.

2.2.2 Method of Supplying Catenary

On the NY, NH & H system and the Reading system autotransformers are used. On the first system, the 11 kV generated voltage is stepped-up to 22 kV by an autotransformer, with the center-tap grounded to the rail (Fig. 2.4). The wire attached to one end of the autotransformer acts as the trolley wire, while the wire attached to the other end functions as the return feeder. Autotransformers are then spaced along the wayside with the trolley and feeder wires connected to the ends and the center taps grounded to the rail. The use of the higher potential (22 kV) across the autotransformers was implemented. This approach using autotransformers has been adopted by both France and Japan on their new electrified rail lines operating at the power utility frequency (50 and 60 Hz).

2.2.3 Track Sectioning Details

Track sectioning equipment is provided so that a section of catenary can be isolated as necessary for maintenance purposes.

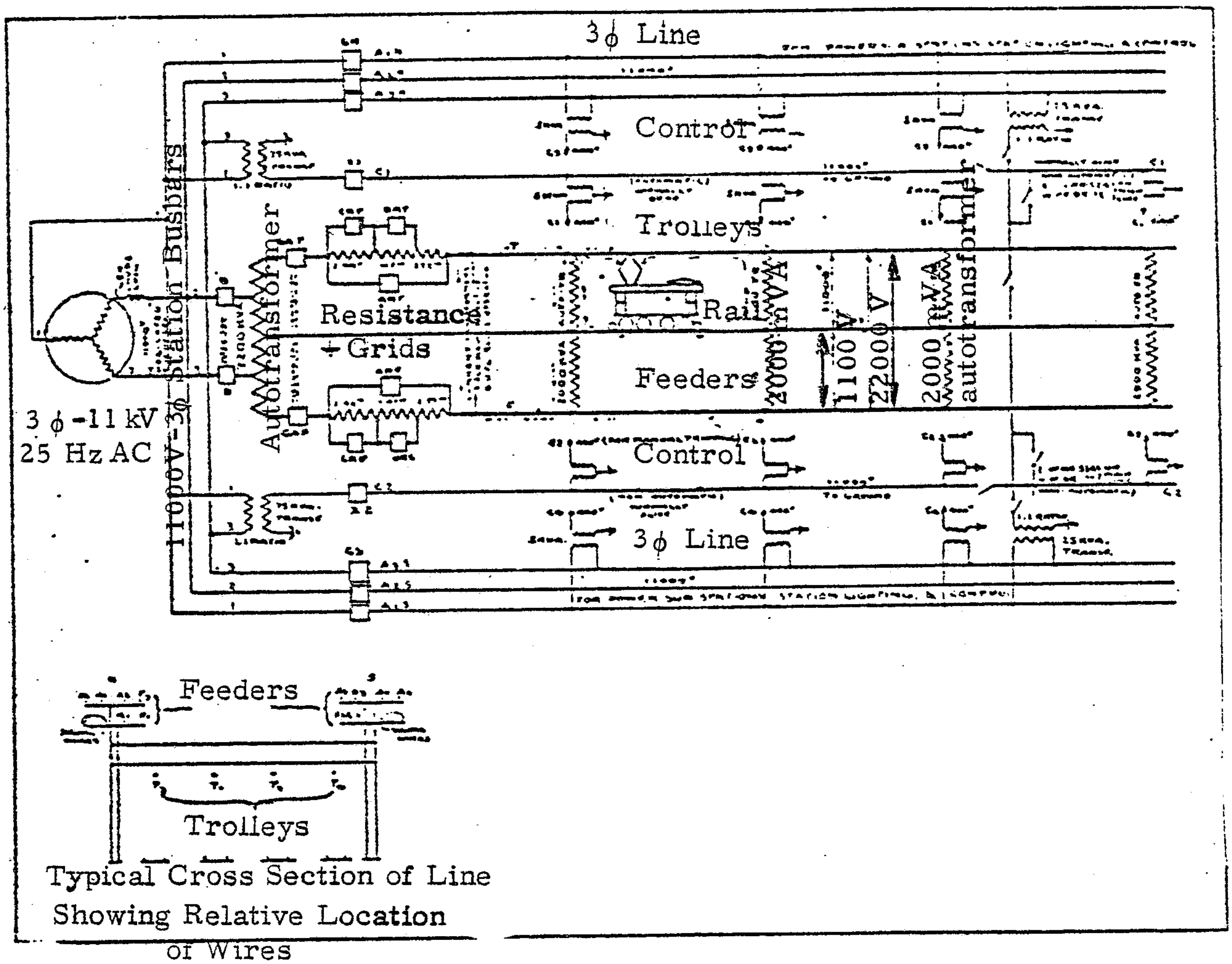


Fig. 2.4 Electrical Schematic Diagram of Distribution System - Former NY, NY & H Railroad

[Note autotransformer connections]

(Ref. 2.4)

2.3 New Haven Line 12 kV 60 Hz

Equipment for the conversion of the New Haven Line between New York and New Haven has been recently installed. However, the change from 11 kV 25 Hz electrification to the 12 kV 60 Hz system has not yet taken place, and operation at the new conditions is not scheduled until 1981. The Connecticut Department of Transportation is responsible for the conversion project.

2.3.1 Source of Electric Power

The railroad is supplied from the local utility at three locations: Cos Cob, Peaceable and Devon. Power at 115 kV is delivered by the utility, which is responsible for all the 115 kV equipment as well as the 25 kV supply breakers it has installed at these three substations. Two of the substations contain two single-phase transformers for each catenary supply bus, each fed by an independent transmission line (Fig. 2.5). The third substation (Cos Cob, Fig. 2.6) contains two pairs of transformer connections: one pair connected open-delta-open-wye is used to supply power in one geographical direction, while the other pair, connected single-phase, supplies power in the other direction. The two different transformer configurations are used at the Cos Cob substation to minimize loading on any individual phase of the utility system.

2.3.2 Method of Supplying Catenary

The railroad substations obtain single-phase power from cables connected to the utility substation. At the railroad substation these cables are connected across the autotransformers by way of the feeder supply bus and the trolley (catenary) supply bus (Fig. 2.7).

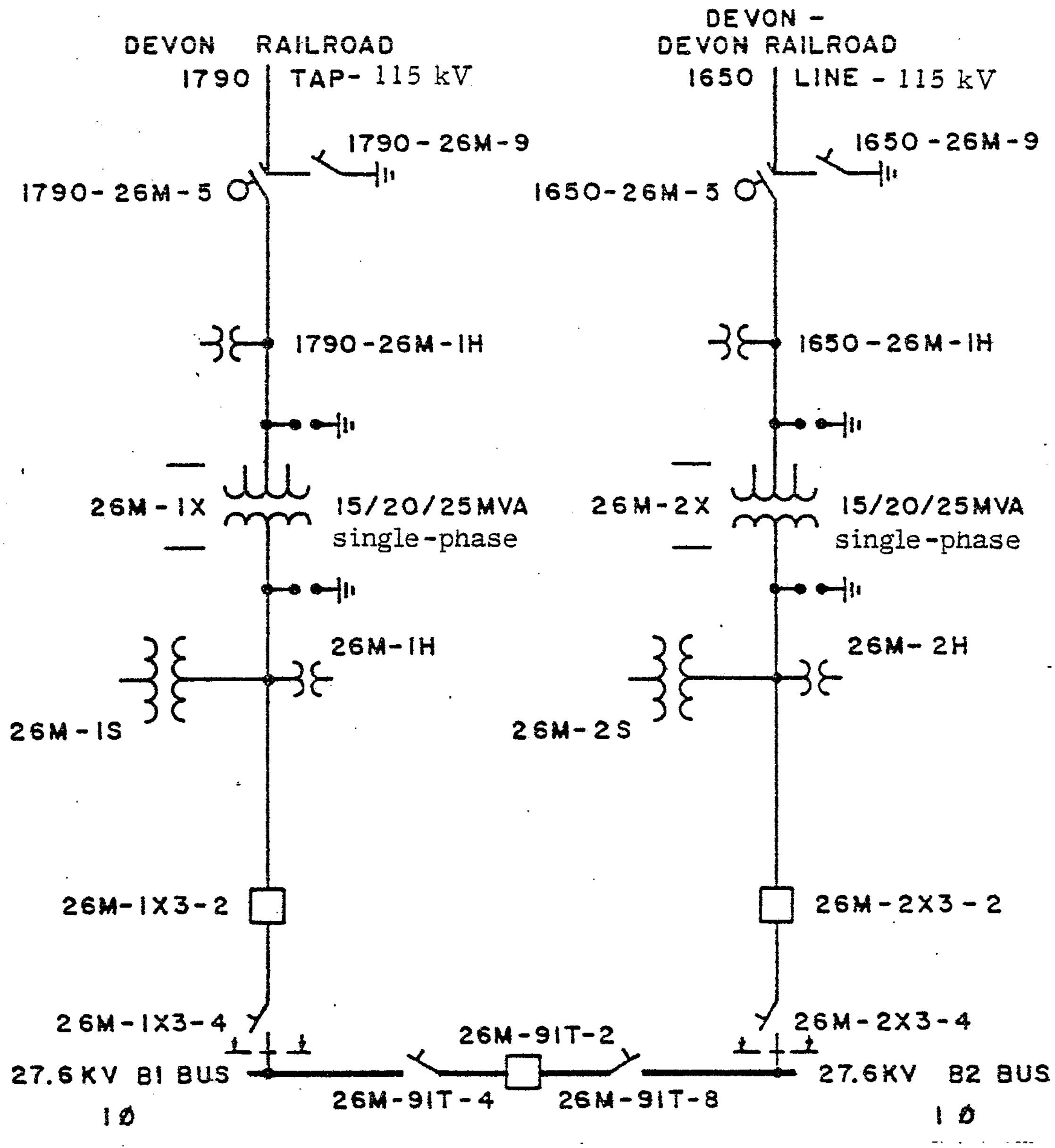


Fig. 2.5 Devon Substation of the 12 kV 60 Hz New Haven Line (Ref. 2.6)

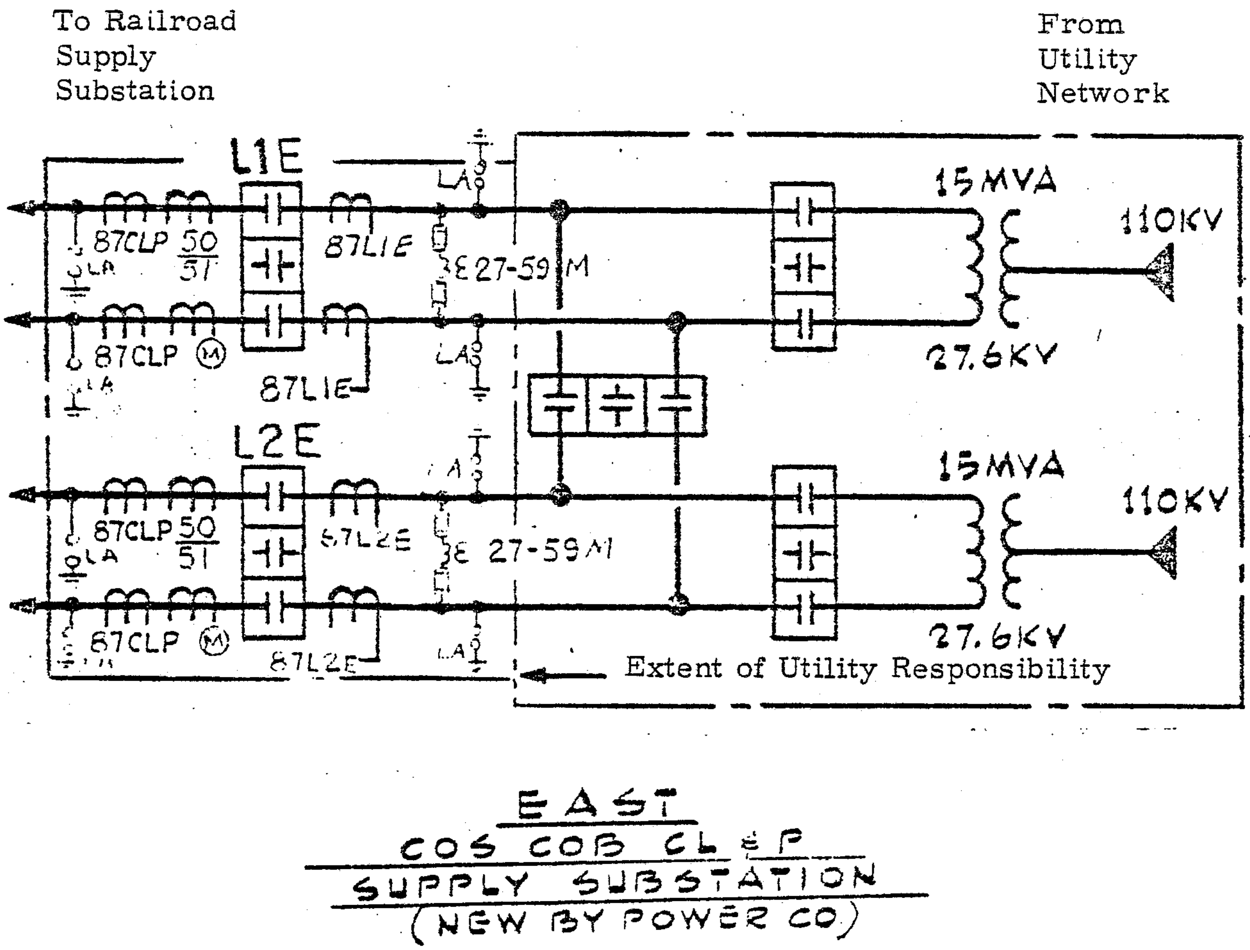


Fig. 2. 6 The East Half of the Utility Supply Substation at Cos Cob (New Haven Line) (Ref. 2. 7)

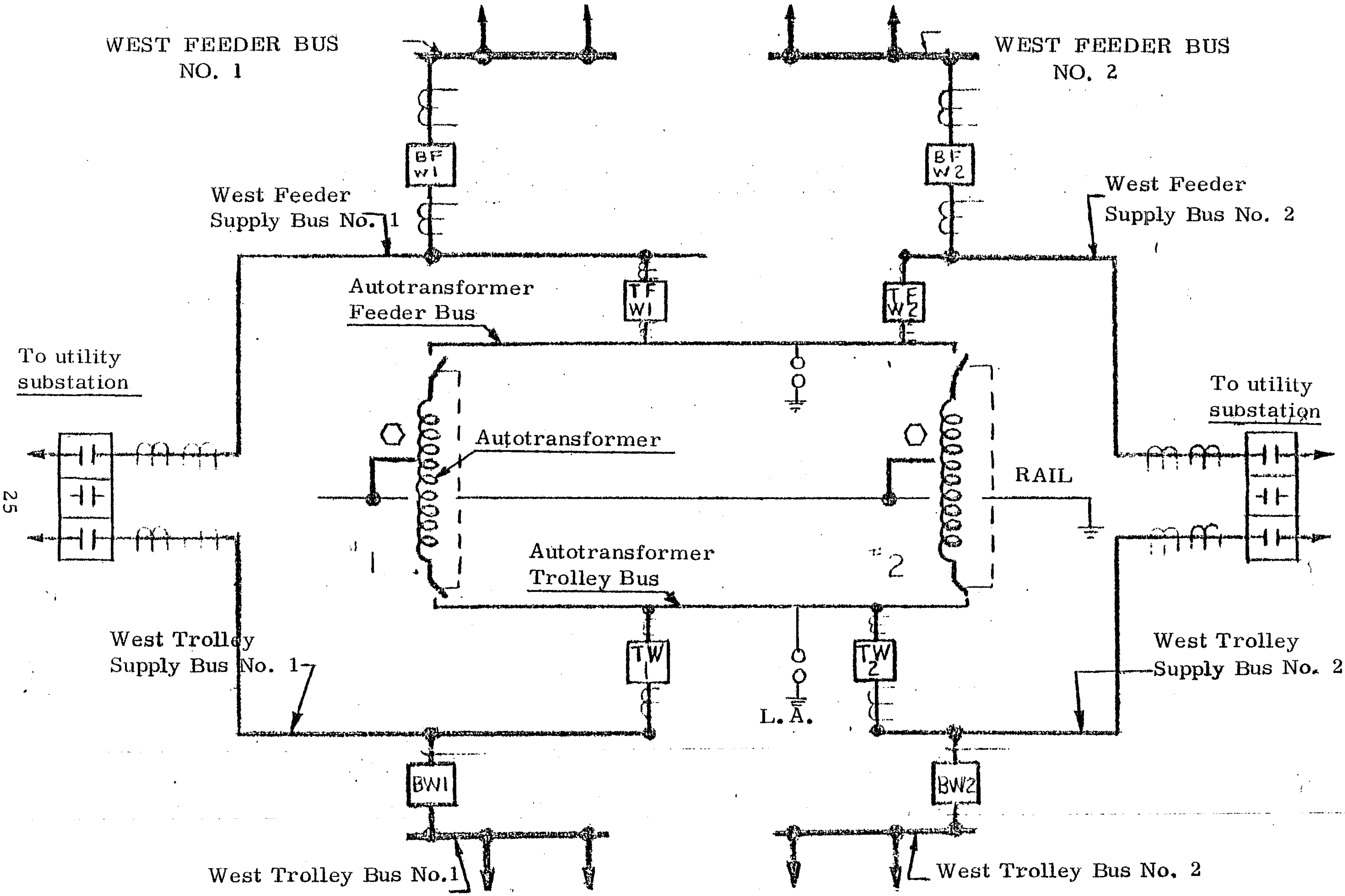


Fig. 2.7 West Portion of Cos Cob Railroad Substation Illustrating the Autotransformer Connections (New Haven Line) (Ref. 2.7)

Insulated feeder cables are connected to the feeder supply bus and span the lengths along the wayside between the railroad autotransformer substations, which are spaced four-to-six miles apart. The trolley wires are connected to the trolley supply bus; they follow the same route as the feeder cables. Using this supply system, the voltage across the autotransformer is double the voltage between the trolley wire and the rail. An increase in substation spacing and reduced electromagnetic interference are two advantages of this system.

2.3.3 Track Sectioning Details

Phase breaks are located at the Cos Cob substation, Norwalk and at a point located between Wilton and Norwalk on the New Canaan branch. A 90° phase shift exists across the phase break at Cos Cob due to the different transformer configuration while a 120° phase shift exists across the other two phase breaks. These divisions separate the different phases of the utility supply.

Section breaks are located at each of the connection points with the trolley wire so that sections of trolley wire can be deenergized for maintenance.

2.4 The Muskingum Electric Railroad - 25 kV 60 Hz

The Muskingum Electric Railroad is the first railroad in the western hemisphere to utilize a 25 kV 60 Hz catenary supply. [This 25 kV commercial frequency design has been widely used in Europe and elsewhere.] The railroad is dedicated to the hauling of coal from a mine to an electric power plant and encompasses a total of 24 route-km of track.

2.4.1 Source of Electric Power

The railroad is served from the Ohio Power Company's South Cumberland Station (Fig. 2.8), which is supplied from the South Caldwell Station 10.2 miles away by a single-circuit 138 kV line. The 138 kV line connections at South Caldwell Station, are made using two motor-operated air-break switches, installed to provide automatic line sectionalizing in the event of permanent faults on the main 138 kV line. Principal South Cumberland Station facilities devoted to railroad supply are a 138/25 kV, 7500 kVA single-phase transformer and a 25 kV vacuum circuit breaker. Two 138/25 kV transformers are specially designed for railroad service. Each transformer has fixed taps on its 138 kV winding to obtain variations in catenary voltage up to ± 5 percent in steps of 2.5 percent. The transformers are not equipped with any automatic 25 kV voltage regulating equipment, since no requirement for 25 kV voltage regulation was anticipated.[2.8]

2.4.2 Method of Supplying Catenary

Since there is only one supply point, no special arrangements are required to energize the catenary.

2.4.3 Track Sectioning Details

No track sectioning is required since only one supply point exists.

2.5 Texas Utilities Railroad - 25 kV 60 Hz

The Texas Utilities Railroad was built for the purpose of hauling coal from a mine to an electric power plant. A total of 42 route-km are installed for this operation.

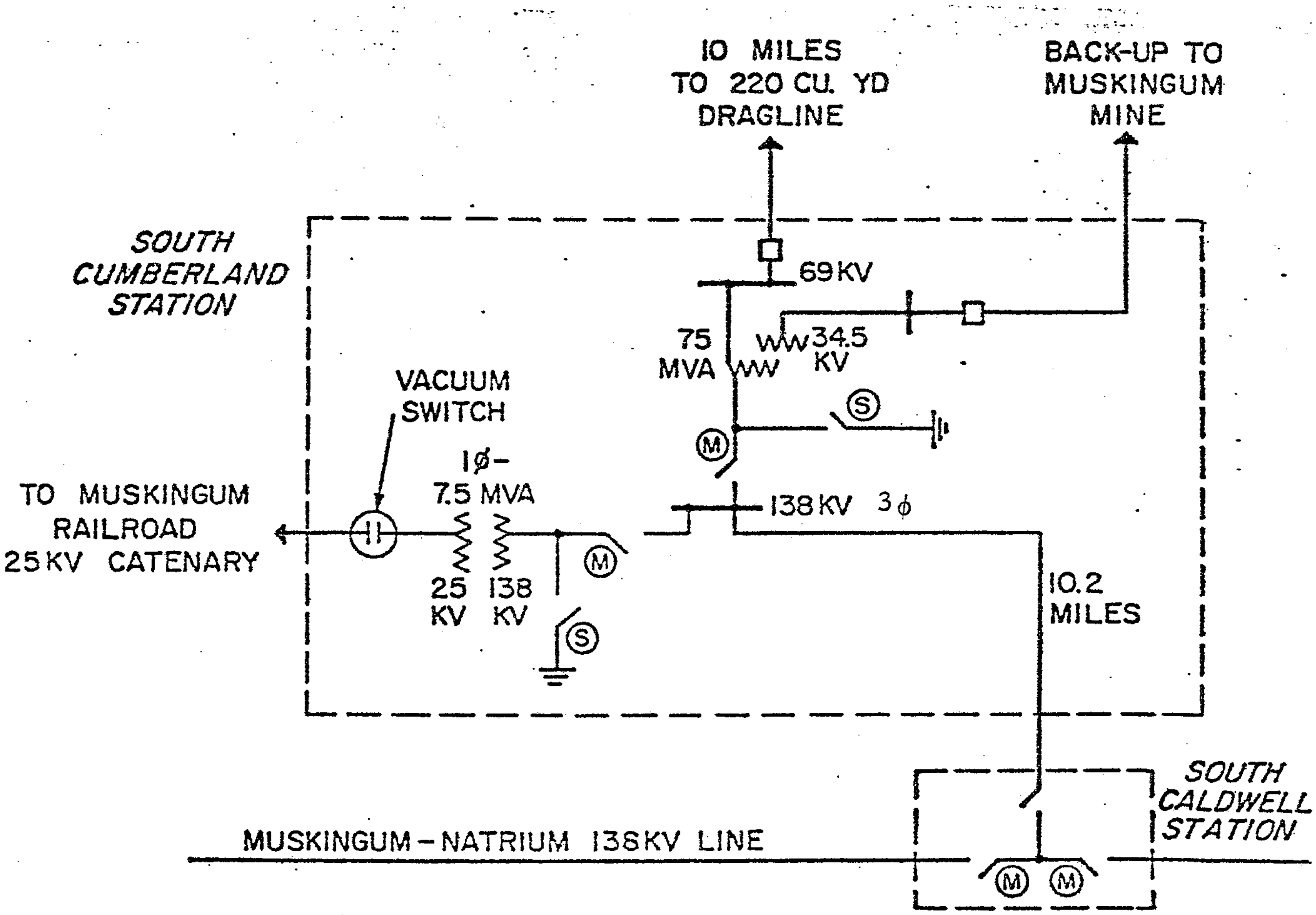


Fig. 2.8 Substation Schematic for 25 kV 60 Hz Electrification System (Muskingum Railroad) (Ref. 2.8)

2.5.1 Source of Electric Power

The railroad is supplied from one substation, which is fed at 138 kV. The two lines which tap the three-phase system at the substation (Fig. 2.9) are connected, via a motorized disconnect switch, to a pair of single-phase step-down transformers which are used to obtain the 25 kV catenary voltage.

2.5.2 Method of Supplying Catenary

From the 25 kV side of the transformers the power is fed through a redundant pair of vacuum breakers to the catenary.

2.5.3 Track Sectioning Details

Since only one supply point exists, no special track sectioning equipment is needed.

2.6 FRA Test Track at Pueblo, Colorado - 13/26/52 kV 60 Hz

The FRA has constructed a test track at Pueblo, Colorado so that vehicles and other equipment used for railroad electrification can be tested and evaluated under controlled conditions.

2.6.1 Source of Electric Power

Southern Colorado Power provides power to the DOT switchyard at 115 kV. The switchyard bus is tapped (Fig. 2.10) and a three-phase 115 kV line is brought to the traction substation.

2.6.2 Method of Supplying Catenary

At the traction substation, single-phase power is connected to a special power transformer through a 2-pole disconnect switch and a vacuum breaker. This special transformer allows the catenary to be energized at 13, 26 or 52 kV, depending on the connection of the

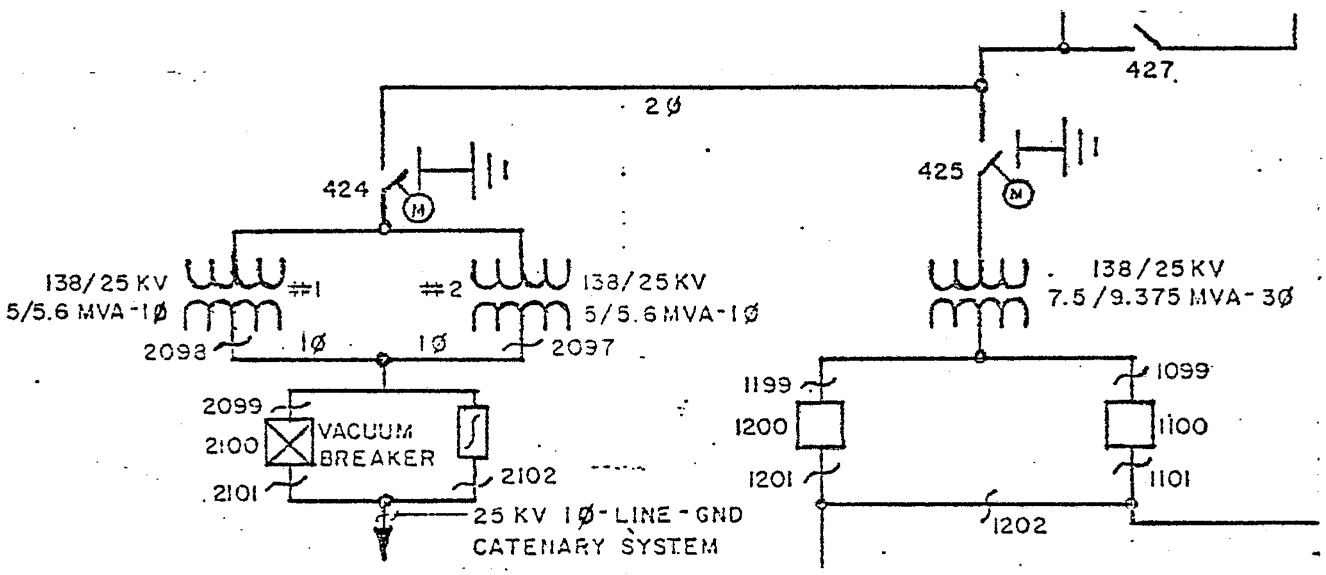


Fig. 2.9 Texas Utilities Railroad Substation Layout (Ref. 2.9)

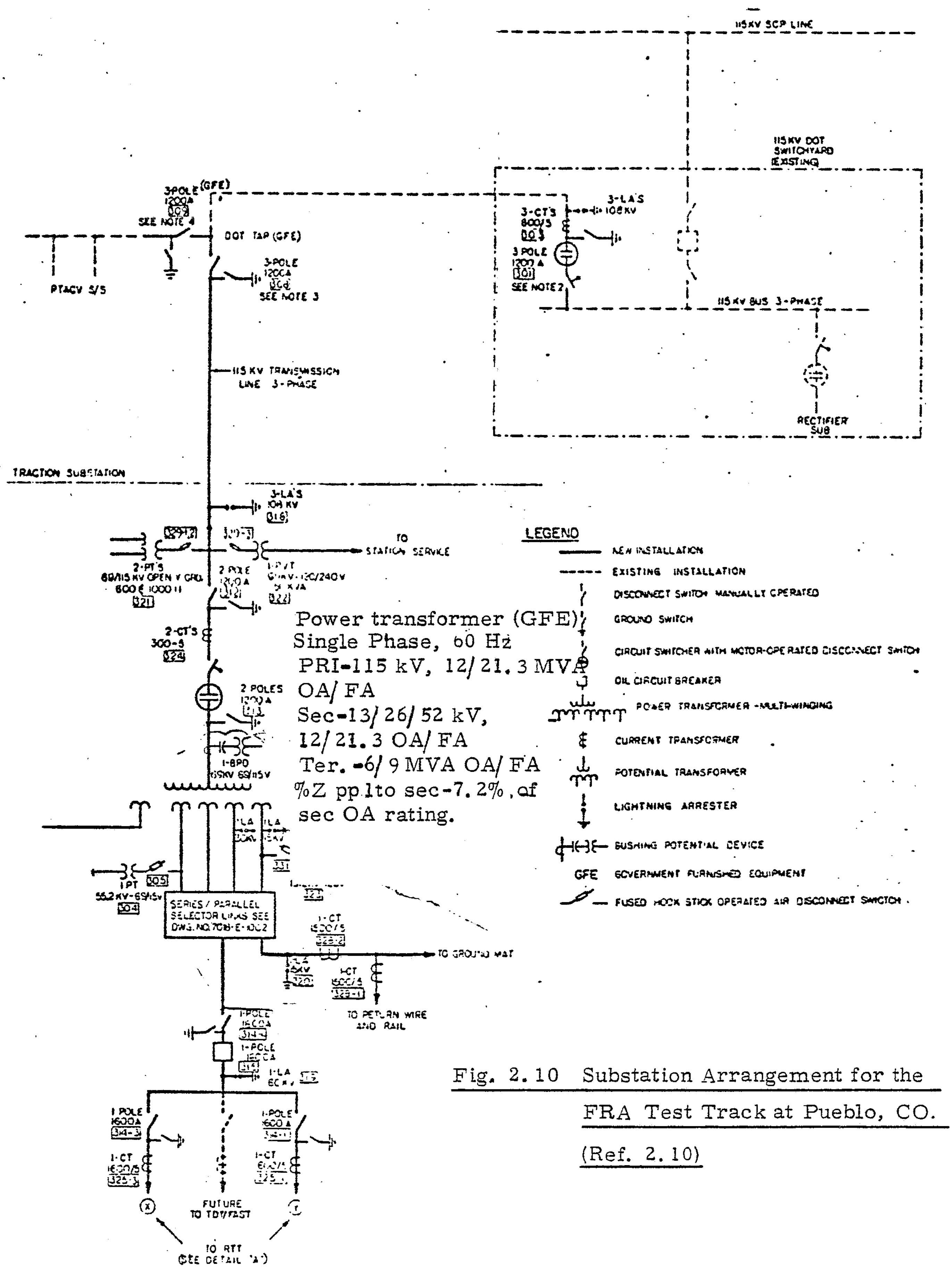


Fig. 2.10 Substation Arrangement for the FRA Test Track at Pueblo, CO. (Ref. 2.10)

series/ parallel selector links in the secondary circuit. The catenary system is supplied by only one phase, even though it is fed by two individual supply lines separated by phase breaks.

2.6.3 Track Sectioning Details

Since only one phase is supplied to the catenary, phase breaks are not needed; however, due to maintenance and test reasons, two phase breaks and one sectionalizing switch have been installed in the catenary system.

2.7 Erie Lackawanna Railroad - 25 kV 60 Hz

The Erie Lackawanna Railroad will be converted from its 3000 V dc operation to an electrification system of 25 kV 60 Hz. At this time (12/ 78) the preliminary design for the new system has not been finalized. However, the following information is available on the proposed system.

2.7.1 Source of Electric Power

The source of electric power for the Erie Lackawanna will be the wayside local utilities. Supply voltages and substation locations will be available in the near future.

2.7.2 Method of Supplying Catenary

The substation will step down the utility voltage to a nominal level of 50 kV, which will be used with an autotransformer catenary supply system, similar to that being installed on the New Haven Line. A typical arrangement of the proposed catenary supply is provided in

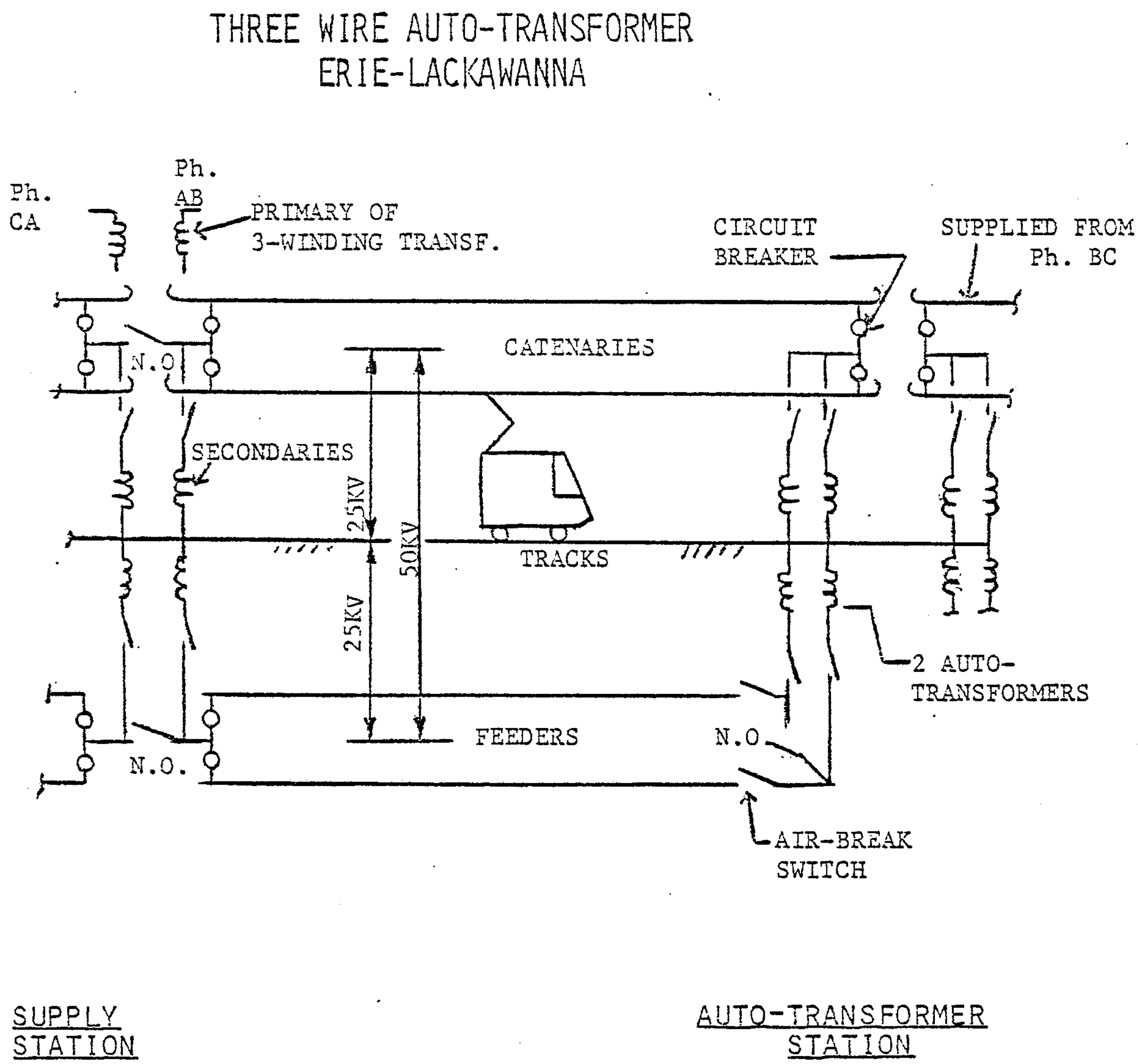


Fig. 2.11 Electrical Schematic Diagram of Proposed Catenary Supply System for Use on the Converted Erie Lackawanna Railroad (Ref. 2.11)

Fig. 2.11. The substation will deliver power to the catenaries using and end-feed method for supply. Different phases will be used for feeding in each geographical direction. Phase breaks will occur at the autotransformer stations and at the substations.

2.7.3 Track Sectioning Details

Air break switches and circuit breakers will be installed in the system to protect the electrical equipment and allow sections of catenary to be isolated for maintenance purposes.

2.8 Northeast Corridor - 25 kV 60 Hz

The preliminary design report for the Northeast Corridor Project has recently been released (12/78).[2.12] A map of the route is provided by the solid dark line in Fig. 2.12. The Northeast Corridor Project will convert the main line between Washington and New Haven from its present operation at 11 kV 25 Hz to operation at 25 kV 60 Hz with a section in Connecticut at 12 kV. The section between New Haven and Boston, which is not electrified at present, will also be electrified to operate at 25 kV 60 Hz. The project timetable calls for operation using 25 kV 60 Hz power by 1981.

2.8.1 Source of Electric Power

The Northeast Corridor will be served by the abutting utilities from their 115 kV, 138 kV, 230 kV, and 345 kV networks. Substation locations have been proposed, and will be finalized shortly.

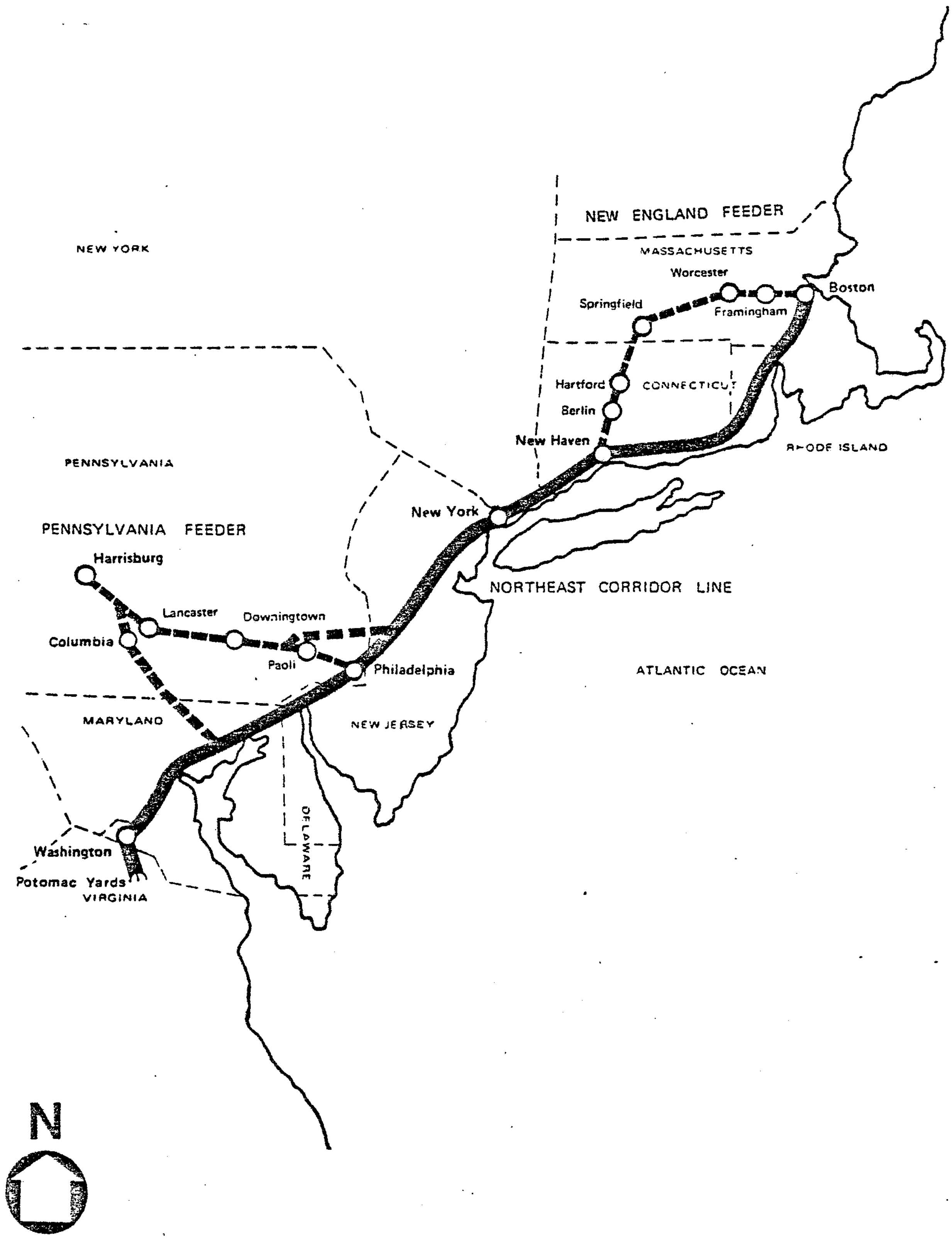


Fig. 2.12 The Northeast Corridor (Ref. 2.12)

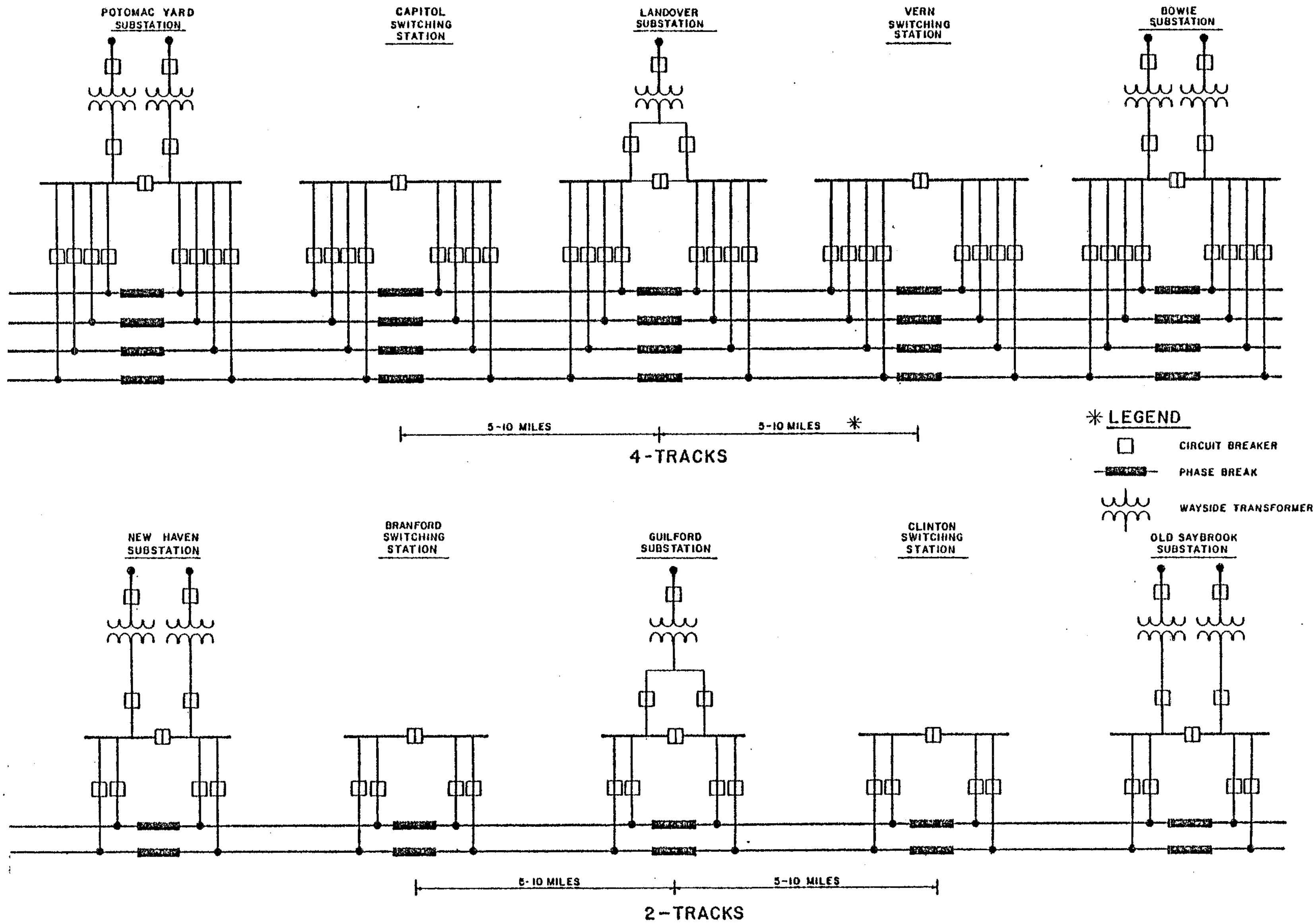


Fig. 2.13 Typical Arrangement of the 4-Track and 2-Track Catenary Supply System for Use on the Northeast Corridor (Ref. 2.12)

2.8.2 Method of Supplying Catenary

The catenary is supplied from substations with one or two transformers, depending upon the load (Fig. 2.13). The catenary is center-fed to minimize equipment requirements and to permit the use of an uncomplicated protection scheme. Substation are generally spaced 10-to-15 miles apart.

2.8.3 Track Sectioning Details

Phase break equipment is located at the substations and at the switching stations, which are located midway between these substations. Under normal operating conditions, the phase break occurs at the switching stations. In the event of a substation outage, the phase break is shifted to allow the catenary to be energized by the adjacent substation.

Circuit breakers, located at the substations and the switching stations, allow a section of catenary to be disconnected for maintenance work or fault isolation.

2.9 Black Mesa & Lake Powell Railroads - 50 kV 60 Hz

The Black Mesa & Lake Powell Railroad (BL&LP) is a dedicated coal-hauling high-voltage line and a part of the Navajo Project. This project consists of the 127 km railroad, three 800 MW generating units, and approximately 1255 km of 500 kV transmission line. The BM&LP is the primary means of transporting coal from the Black Mesa mine in northern Arizona to the generating station near Page, Arizona (at the edge of Lake Powell) 127 km away.[2.13]

2.9.1 Source of Electric Power

The remoteness of the mine and the lack of their available power sources led to the decision to operate the railroad electrically from a single power source near the generating station. This approach resulted in the world's first 50 kV ac single-phase electrified railroad. The initial power supply consisted of one substation with two 10 MVA, 230/50 kV single-phase transformers operating in parallel. The inductance of the electric catenary was series-compensated with a 10 ohm capacitor bank located at the substation. The initial one-line configuration is shown in Fig. 2.14 A.[2.13]

2.9.2 Method of Supplying Catenary

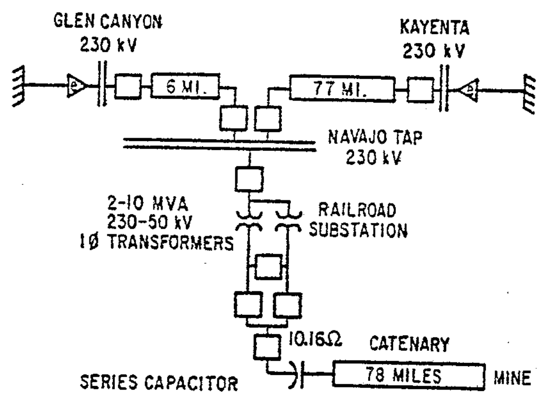
Since only one substation exists, no special supply arrangements were needed initially, except for the 10 ohm capacitor. However, after a few years of operation, the railroad was uprated to double its hauling capacity without the addition of substations or transmission lines. This uprating was accomplished by installing filters at one location along the track (to minimize the harmonic requirements of the substation) and by installing two series capacitor banks (to compensate for the catenary inductance)(Fig. 2.14B).[2.13]

2.9.3 Track Sectioning Details

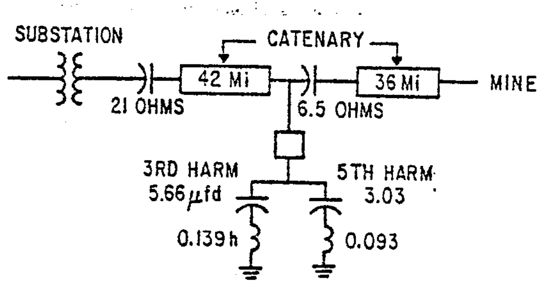
No track sectioning is required, since only one supply substation exists.

2.10 Summary

In the United States three different electrification systems are in operation. The dedicated 11 kV 25 Hz system which is slowly being phased out in the northeast currently supplies power to 67 substations along



A Existing utility and railroad system



B Final catenary modification

Fig. 2.14 Electrical Schematic Diagram of the Initial (A) and Final (B) Configurations of the Catenary Supply System for the Black Mesa and Lake Powell Railroad (Ref. 2.13)

530 route km of track from special generation and 132 kV transmission installations. The substations have at least two transformers to step the power down to the 11 kV level, and are spaced about 16 km apart. The New York, New Haven and Hartford Railroad and the Reading Railroad (former) use the autotransformer catenary supply system on their 11 kV 25 Hz system. The utility-supplied 60 Hz power is currently used on three dedicated coal haul lines: the Muskingum, the Black Mesa & Lake Powell (BM&LP) and the Texas Utilities Lines. Each line is fed from only one substation, and the catenary voltage of 25 kV is used by the Muskingum (24 route km) and Texas Utilities (42 route-km), while 50 kV is used on the BM&LP (125 route-km). The FRA has built a 13/26/52 kV test track in Pueblo, Colorado to evaluate equipment for future electrification. New lines that have not begun operation but will use 60 Hz power are the 12 kV New Haven Line, the 25 kV Erie Lackawanna Line, and the 25 kV Northeast Corridor.

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3.0 UNITED KINGDOM

British Railways (BR) decided in 1955 to electrify their high traffic density rail lines with 25 kV 50 Hz power taken from the 132 kV National Grid. This decision was based on the savings possible through use of smaller overhead conductors, lighter supports and longer feeding sections, when compared to the dc systems in use at that time. The United Kingdom has standardized on this electrification system.

The map provided in Fig. 3.1 shows the main electrified lines in the United Kingdom as of 1967. Table 3-1 presents data on all of the electrified ac lines in the United Kingdom as of 1977.

3.1 Source of Electric Power

The length of feeding sections are determined primarily from consideration of the traffic to be handled, the performance required of the electric traction equipment and the electrical characteristics of the overhead and supply systems. Such considerations result in an optimum spacing which it is not often possible to achieve and the desirability of locating the feeder stations at strategic points such as junctions or route intersections frequently results in a shorter spacing being used. Again, the feeder stations are preferably situated in close proximity to Grid substations in order to avoid the disadvantages of long feeders. Generally the Grid substations are of necessity located near to the large towns, which in this country are situated relatively close together.[3.1]

Fig. 3.1 Map of Electrified Lines in the United Kingdom. (Ref. 3.4)

Table 3-1

Extent of AC Electrification in the United Kingdom as of 1977. (Ref. 3.6)

System of Electrification: D.C.=Direct current; A.C.=Alternating current; 1/50=Alternating current, 1-phase, 50 cycles, 3/16⅔=Alternating current, 3-phase, 16⅔ cycles, etc.
Conductor: 3 R=Third rail; 4 R= Third and fourth rail, side conductor rail with centre rail return; O H=Overhead, etc.

Country, Railway, and Lines Electrified	Length Electrified		Voltage	System of Electrification	Conductor	Year Electrified
	Route Km.	All Track Km.				
Great Britain—						
Eastern Region—						
Liverpool Street - Gidea Park	22	132	6·25 kV	1/150	O H	1949 D.C.; to A.C. 1960
Gidea Park - Shenfield . . .	10	45	25 kV	1/50	O H	1976 Uprated to 25kV A.C.
Shenfield - Southend (Victoria)	34	89	6·25 kV	1/50	O H	1956 D.C to A.C. 1960
Shenfield - Chelmsford . .	16	32	25 kV	1/50	O H	1956 D.C.; to A.C. 1961
Chelmsford - Colchester .	37	90	25 kV	1/50	O H	1962
Colchester-Clacton-Walton .	39	77	25 kV	1/50	O H	1959
Liverpool St. - Chingford - Enfield Town-Cheshunt	37	92	6·25 kV	1/50	O H	1960
Clapton Junc.-Cheshunt Jnc.	14	31	25 kV	1/50	O H	1969
Cheshunt - Bishops Stortford - Hertford East	37	87	25 kV	1/50	O H	1960
Fenchurch St.-Southend (Central)-Shoeburyness-Tilbury Riverside	119	279	6·25/ 25 kV	1/50	O H	1961–62
Finsbury Pk.-Welwyn G.C. .	31	143	25 kV	1/50	O H	1976
Bowes Pk.-Langley Jct. .	34	72	25 kV	1/50	O H	1975
Dunford Bridge - Sheffield - Wath-Tinsley	69	234	1,500	D.C.	O H	1951–54; 1965
Total, Eastern Region .	409	1,403	..	..	..	..
London Midland Region—						
Euston to Watford and Croxley Green; Broad Street to Willesden and South Acton	55	116	630	D.C.	4 R and 3 R	1916-22
Liverpool - Southport - Ormskirk	47	108	630	D.C.	3 R	1904-13
Wirral	25	57	650	D.C.	3 R	1903-38
Manchester-Bury . .	16	35	1,200	D.C.	3 R	1916
Manchester-Dunford Bridge	44	151	1,500	D.C.	O H	1951-54
London (Euston) - Birmingham-Liverpool-Manchester	712	2,300	25,000	1/50	O H	1960-67
Weaver Jct.-Gretna Jct. . .	232	640	25,000	1/50	O H	1971-74
Total, L.M. Region .	1,131	3,407	..	..	..	..
Scottish Region—						
Glasgow suburban: North of Clyde	84	172	6·25/ 25 kV	1/50	O H	1960
Glasgow suburban: South of Clyde	47	109	6·25/ 25 kV	1/50	O H	1962
Glasgow suburban: South of Clyde	56	119	25 kV	1/50	O H	1967
Glasgow Central-Eglinton St.	2	4	25 kV	1/50	O H	1971
Motherwell South to Braidhurst via Lesmahagow Junction	10	27	25 kV	1/50	O H	1972
Motherwell South to Gretna Junction	131	278	25 kV	1/50	O H	1973
Uddingston-Law Junction - Mossend - Braidhurst - Ravenscraig Sidings	16	44	25 kV	1/50	O H	1973
Newton - Eglinton St. Gushetfaulds, Hamilton Circle, Shieldmuir, Lanark branch	30	68	25 kV	1/50	O H	1974
West St. Terminus-Muirhouse Junction	2	3	25 kV	1/50	O H	1975
Total, Scottish Region .	373	824	..	..	..	..

Once the site of the feeder stations are established with respect to the 132 kV network, it is then necessary to decide whether single- or double-transformer feeder stations are required, single being preferred as they are cheaper and better able to carry emergency loading which is roughly normal plus 50%, as against normal plus 100% for double. Normal feeding limits for trunk routes on BR have been found to be up to 30 km (distance from one substation) and emergency feeding limits are up to 60 km.[3.2]

At duplicate supplies, two single-phase 132/25 kV transformers are banked, each with the existing Grid transformer, for supplying the distribution system. The railway transformers and distribution transformers have common arrangements for switching on the 132 kV side, but have individually remote-operated 132 kV isolators for easy isolation (Fig. 3.2). The low voltage sides of the railway transformers (25 kV) are provided with isolators and earthing switches, and connected to railway substations by double-circuit 25 kV overhead lines where practicable, or otherwise by 25 kV cable terminating in 2 x 25 kV single-phase circuit-breakers on the railway switchboard (Fig. 3.3). Where an overhead line connection is used, a 25 kV circuit-breaker is also provided at the transformers. The two transformers at a supply point are supplied from the same pair of phases, but at adjacent supply points the phasing would be different. At some of the Grid substations from which it is proposed to power the railway, the distribution transformers are already banked in pairs. At these stations it is also proposed to add the railway transformers by banking. With this approach it has not been necessary to provide 132 kV switches to specially control the railway transformers resulting in a considerable saving of capital expenditure. Examples of single and duplicate supplies are shown in Fig. 3.4.

A range of transformer sizes is used (viz. 15, 10, 7.5 and 5 MVA) to handle a wide range of railroad loads. The short circuit duty of the 132 kV circuit at the point of the supply ranges from 1500 MVA to 3000 MVA at large-capacity stations.

With the 25 kV single-phase railway system it is essential that the security arrangements to each point of supply should be of a high order, especially where no permanent parallel operation is permissible between supply points through the catenary system. For parallel operation through the catenary system to be acceptable, there should be no through-flows which would cause unbalanced conditions on the transmission system.

The use of Scott-connected transformers was considered, but it seemed that there would be no advantage in using them as they produce balanced conditions on the 3-phase system only if both windings on the 2-phase side are equally loaded, which would rarely occur in practice. Single-phase transformers are preferred on account of simplicity and cost, and on the busy railway system the loads taken along its length are expected to produce balanced conditions on the Grid as a whole if the single-phase transformers at the various supply points are supplied from different phases.[3.3]

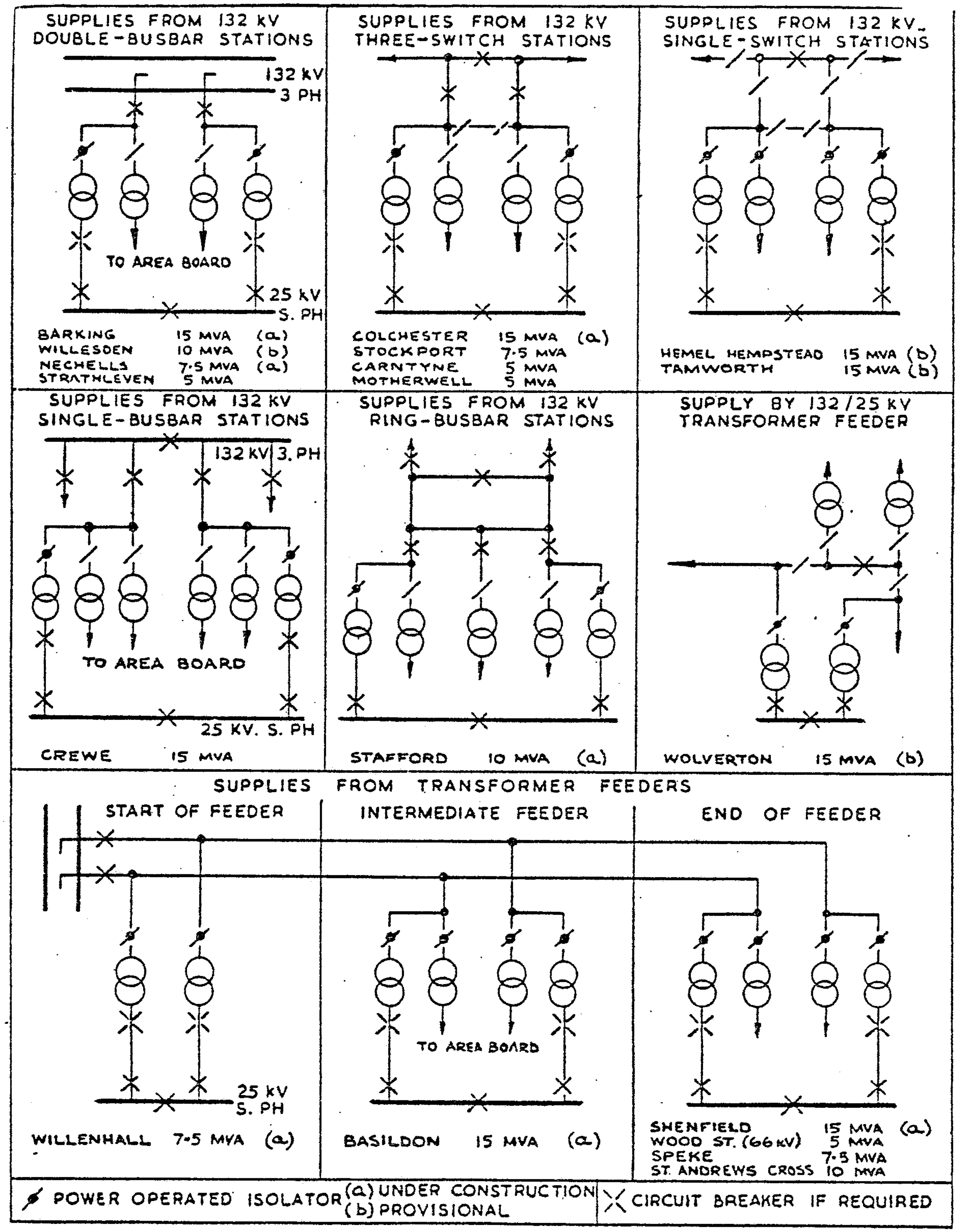


Fig. 3.2 Typical Supply Arrangements Used on the Euston-Manchester Liverpool, London and Suburban, and Glasgow and Suburban Lines. (Ref. 3.3)

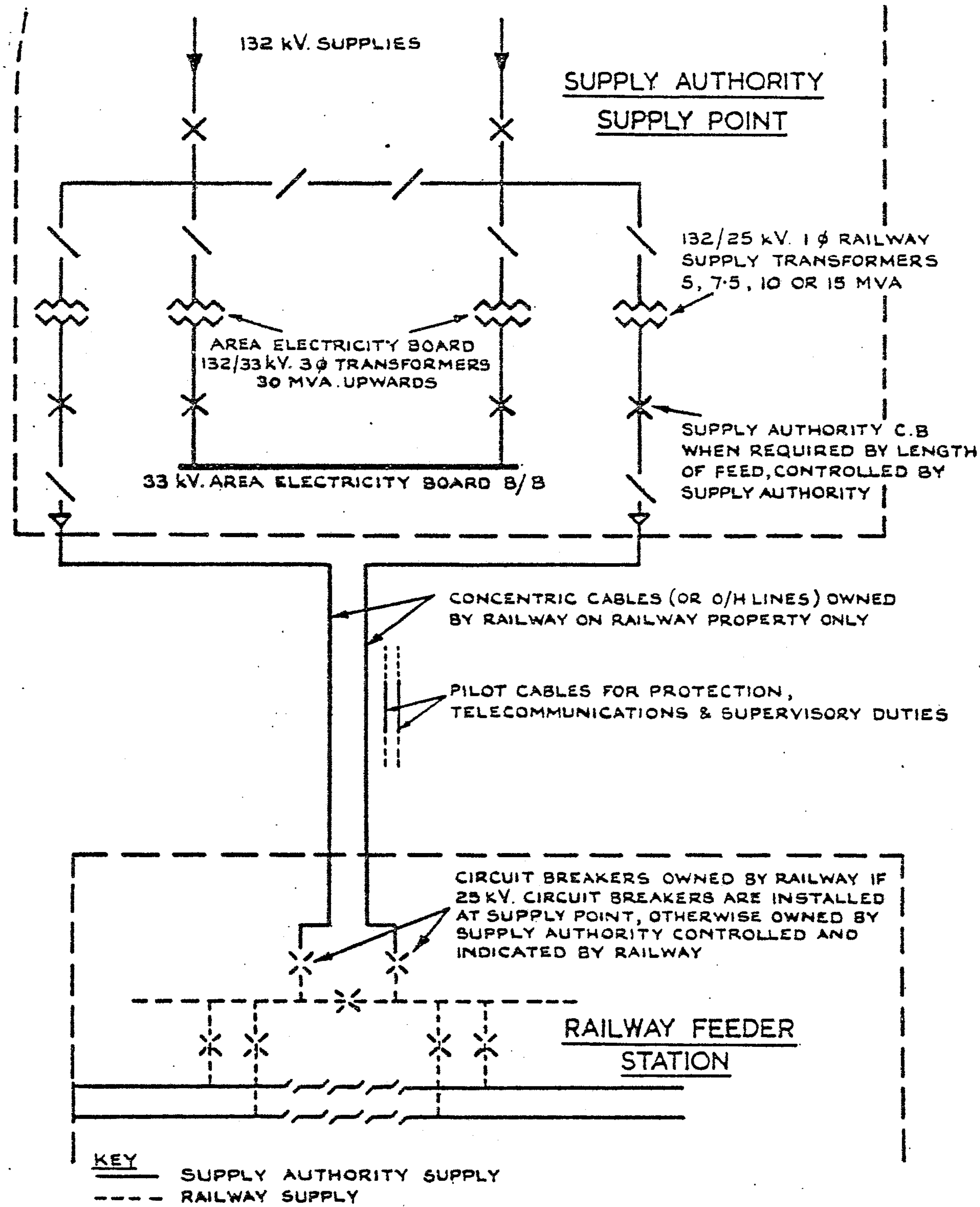
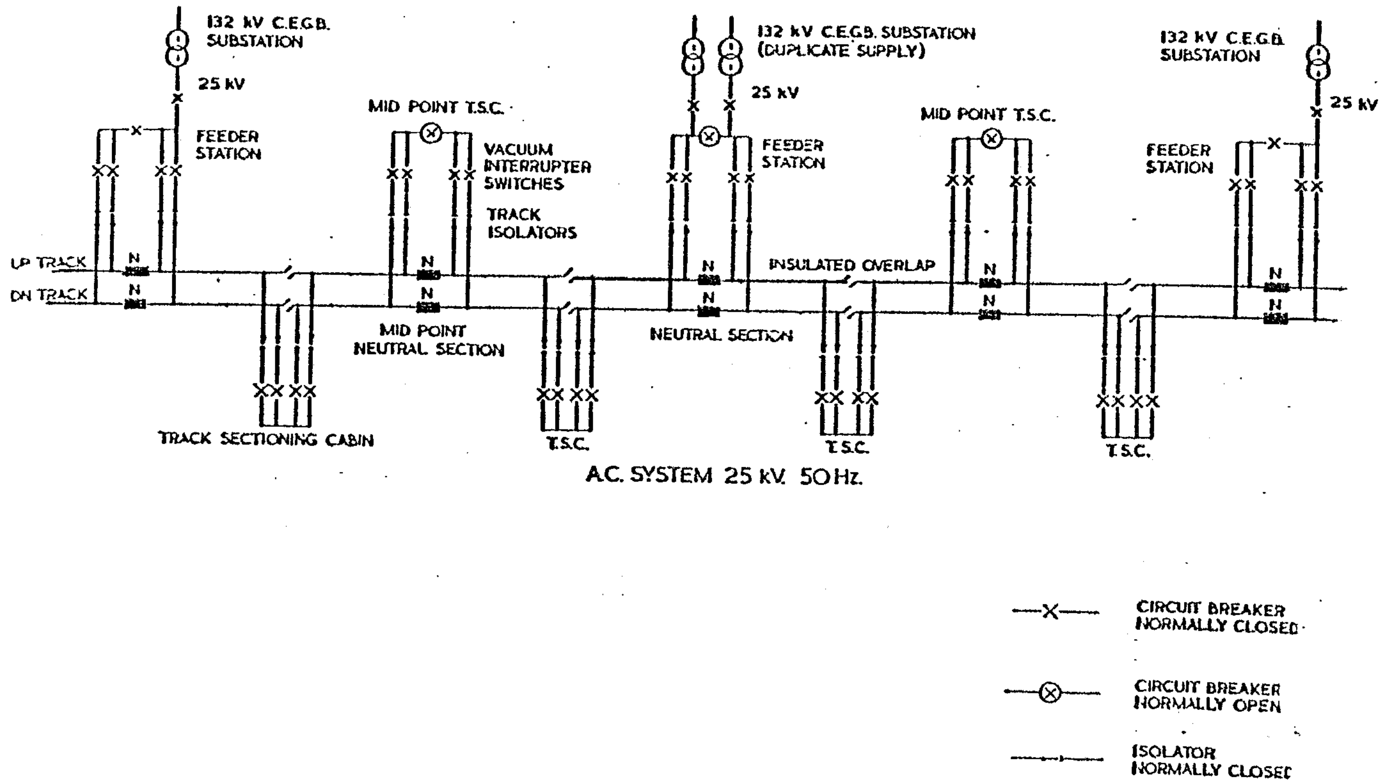


Fig. 3.3 Typical Substation Arrangement Showing Extent of Authority of BR and the C.E.G.B. (Ref. 3.1)



30 km - normal substation spacing

Fig. 3.4 Typical Supply Arrangement Illustrating Single and Duplicate Supplies. (Ref. 3.5)

Earthing at the Central Electricity Generating Board (C. E. G. B.) end of the incoming feeder is provided through a spark gap, normally the 25 kV supply is only earthed at the railway end.

For the inner-city area of the electrification, due to severely restricting tunnel and bridge clearances, the lines are fed at one-fourth the nominal voltage or 6.25 kV. These 6.25 kV supplies are obtained from the normal 25 kV supplies by means of step-down transformers provided by the utility and installed at sub-feeder stations.[3.1]

For the smaller supplies to be provided in London, transformers have been supplied from the distribution systems. In these cases the transformers will be controlled by separate switches or connected off other transformers. Transformers used will be either single-phase, 3-phase or Scott-connected, depending upon load conditions.[3.3]

3.2 Method of Supplying Catenary

Feeder station incoming power is brought in from the C. E. G. B. through oil-filled concentric cables at 25 kV. Feeder station outgoing power is sent from the track feeder circuit breakers to the overhead equipment through single-core solid insulation cables with sealing ends mounted on the overhead line structures.[3.4] Presently, where feasible, the power is brought from a C. E. G. B. substation to a feeder station by overhead conductors and is then passed through bare aluminum rod connections to the manually-operated isolators mounted on the overhead equipment structures.

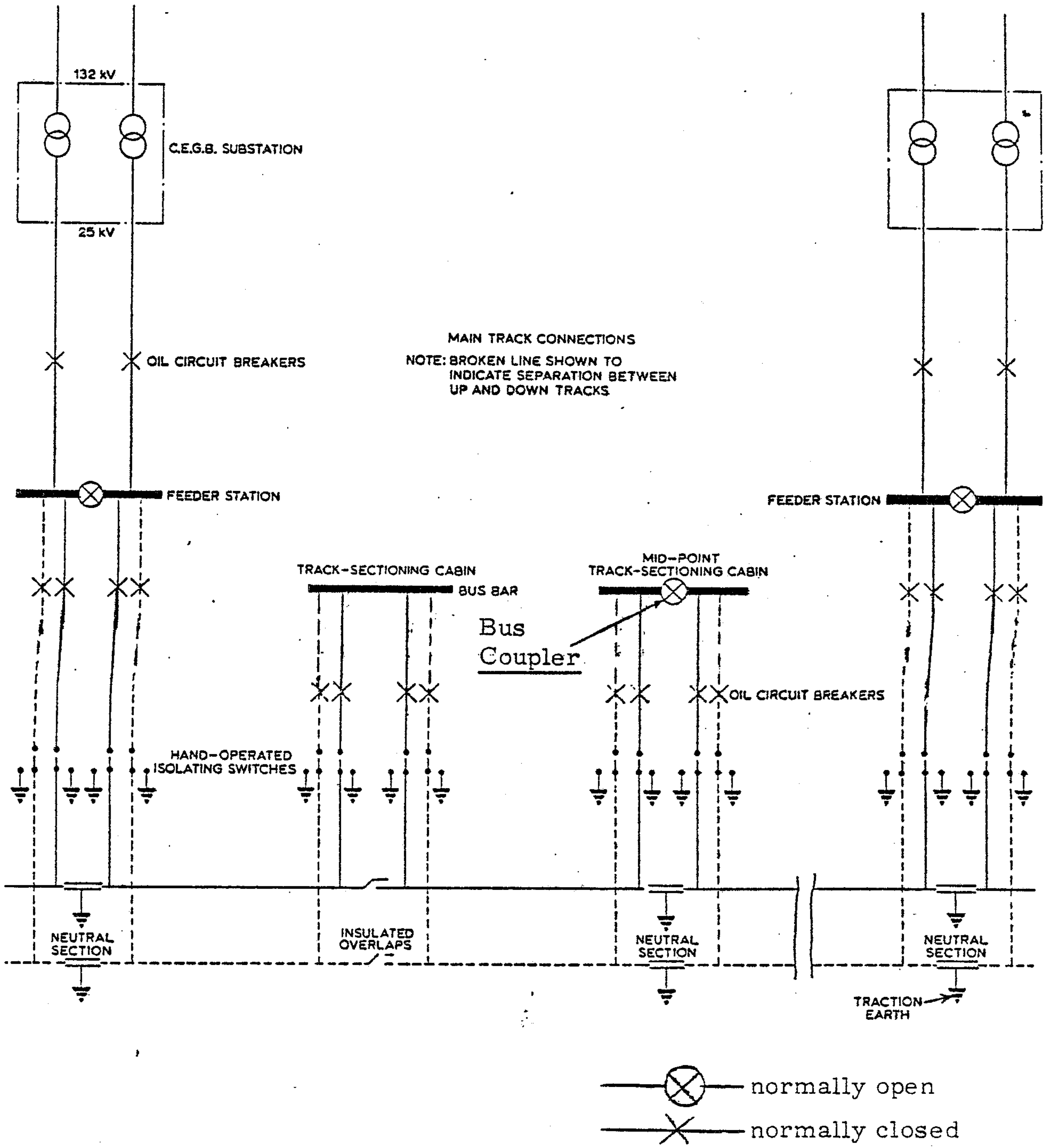


Fig. 3.5 Typical Supply Arrangement Illustrating the Track Sectioning Components. (Ref. 3.4)

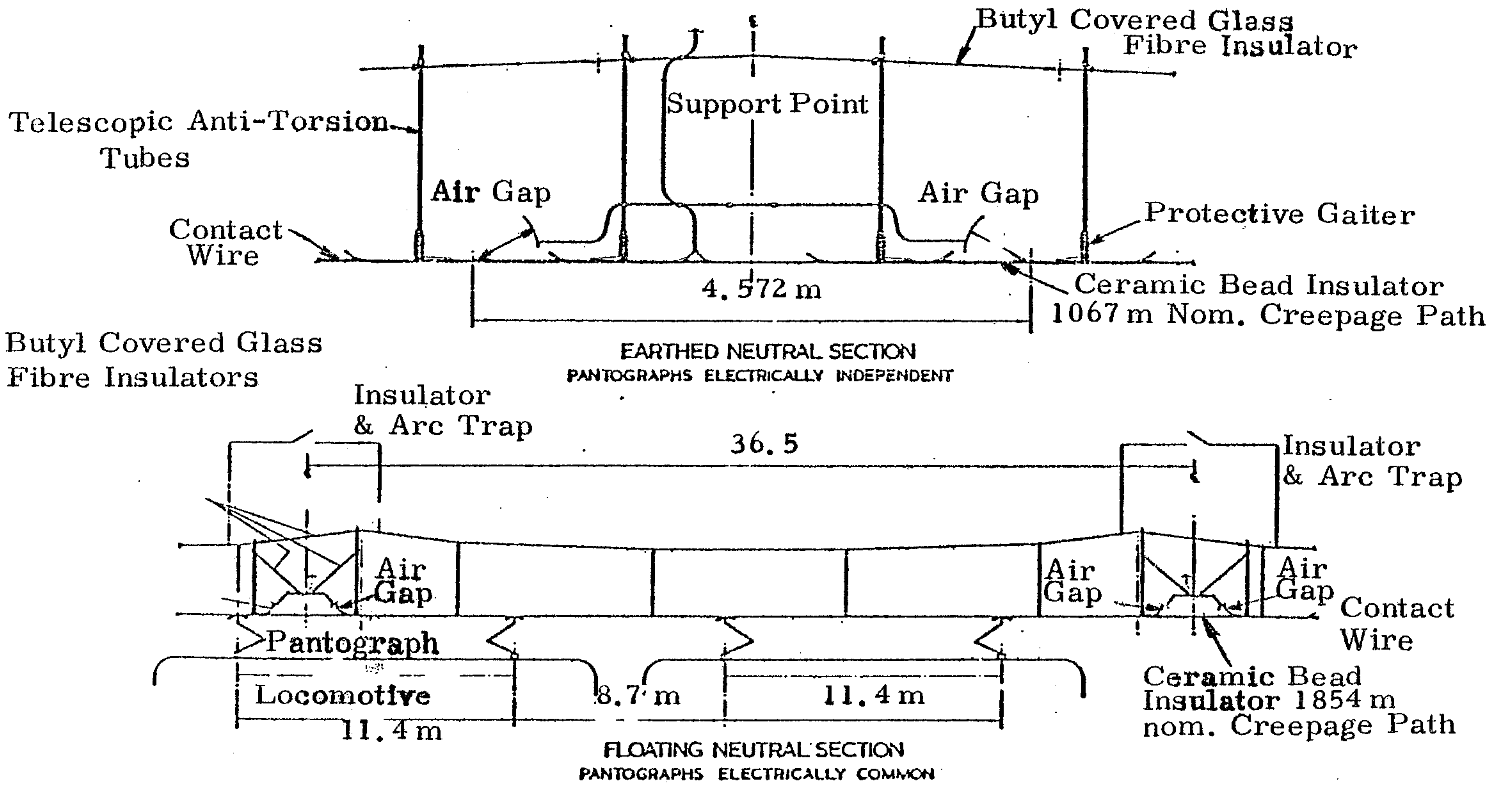


Fig. 3.6 Earthed Neutral and Floating Neutral Sections (Ref. 3.5)

Instead of the oil circuit breakers used on earlier ac schemes, pairs of vacuum interrupters, in series, are sometimes used. Operation is by motor-wound spring, and the complete circuit breaker assembly can be easily disconnected and removed for maintenance.

BR feeds each main line track separately, as shown in Figs. 3.3 and 3.4. When a section of catenary is disconnected from the supply for maintenance purposes, the current is broken by vacuum interrupters and simple track isolators are then operated (Fig. 3.5).[3.5]

The boundary between the areas fed from adjacent feeder stations is generally midway between the stations, and at these points neutral sections are provided to separate the two supplies, which are often on different phases (Fig. 3.5). Neutral sections are also provided at feeder stations, both to divide each area normally fed into two portions (one for each incoming supply) and to provide the facilities of a 'mid-point' to be used under the emergency condition of a feeder station being lost. The neutral section is bridged out when only one of the duplicate supplies is in use.[3.4]

In the neutral sections, British designs use two inrunning ceramic bead insulators, normally separated by a short section of earthed equipment - see Fig. 3.6. If each pantograph is electrically independent, as is normally the case, the compact ceramic bead design is feasible. If, on the other hand, there are two or more electrically connected pantographs on a train, the neutral part of the overhead equipment must 'float' instead of being at earth potential and the insulation must be spaced so that in no circumstances can one phase be connected to another.[3.5]

3.3 Track Sectioning Details

For ac systems using the national generating frequency, a neutral section is provided at the feeding point and at points midway between feeding points. Figs. 3.4 and 3.5 show a network typical of British 25 kV lines. An additional track-sectioning cabin is located between each feeder station and midpoint track-sectioning cabin to permit sections as small as 9 km in length to be isolated for maintenance purposes.[3.5]

Each track sectioning cabin contains a group of single-pole circuit breakers with a bus coupler switch to provide facilities for through-feeding in the event of the loss of supply at the feeder station on either side. This arrangement also allows full advantage to be taken of the overhead conductors over parallel tracks to reduce voltage drops in overhead lines. Midway between each track sectioning cabin and the railway feeder station is located a mid-point track sectioning cabin for added overhead line sectioning. In this way, the zone of disturbance caused by a fault is kept small. Also, in the event it is necessary to isolate a section of the overhead line for maintenance, the length of the line that is isolated is kept within an acceptable limit.[3.1]

Return currents with ac traction are not inherently confined to the running rails, and precautions must be taken to prevent electromagnetic interference with General Post Office (G. P. O.) telecommunications circuits and other equipment located on the roadway. At first, on the Manchester-Crewe line, 1:1 booster transformers, having their primary windings in series with the overhead catenary and their secondaries across insulated joints in the rails, were used to encourage return current to remain in the rails. On later sections of this line, return conductors were provided, one for each track, and the booster transformers drew the current out of the rails and earth into these conductors. Fig. 3.7 shows the connections for these arrangements. Booster transformers, at intervals of 0.6 km with rail return or 1.25 km when return conductors are installed, are mounted about 3 m above ground level on special structures.

In parts of the last areas to be completed, in London and Birmingham, the G. P. O. has agreed to dispense altogether with these special measures, the inherent immunity of their modern equipment being adequate.[3.4]

3.4 Summary

In the United Kingdom 25 kV 50 Hz electrification has been selected as the standard. Power is applied to the 1750 route-km (1977) from the utility's 132 kV network. The catenary is center-fed from single phase transformers at substations spaced about 30 km apart. Neutral sections are located midway between substations, while additional sectioning points exist between these points. Where

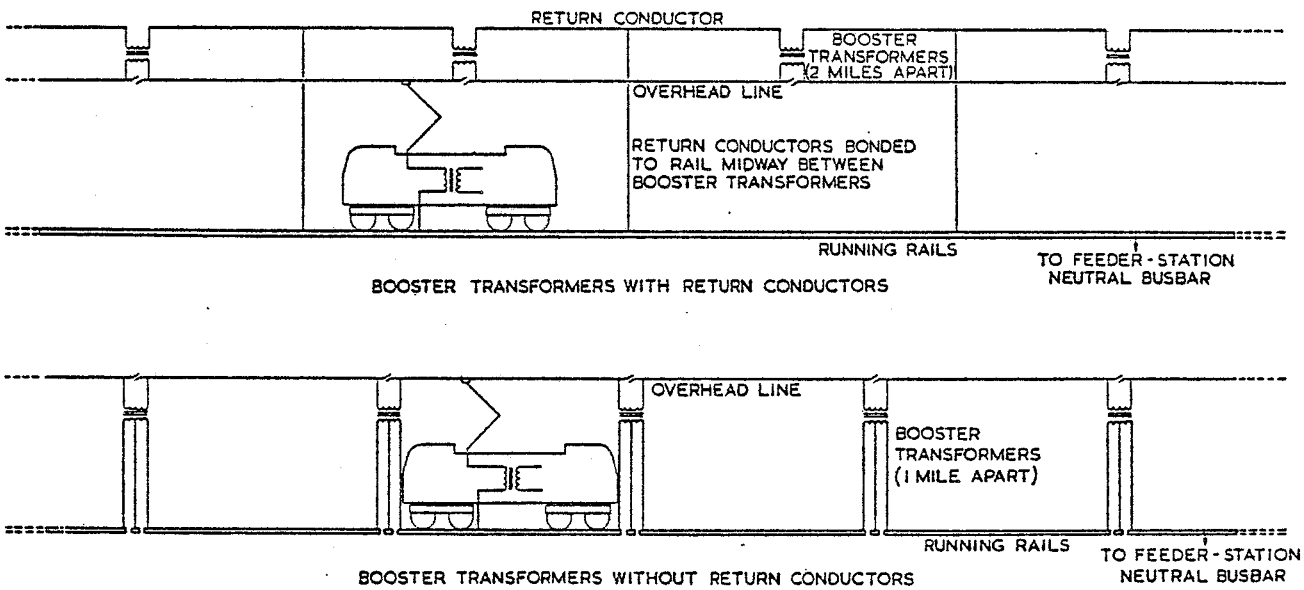


Fig. 3.7 Booster Transformer Connections With and Without Return Conductors. (Ref. 3.4)

insufficient clearance does not permit 25 kV operation,, as in city areas, 6.25 kV is used (200 route-km) as well as center and end-fed sections of catenary and single-phase, 3-phase and Scott-connected transformers, depending upon the load.

3.5 References

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4.0 FRANCE

The French national railway system or the Society Nationale des Chemins de Fer (SNCF) comprises 25,145 route-km, of which 9360 route-km are electrified, as shown in Table 4-1. Approximately half of this system (4530 km) uses single-phase ac power at 25 kV 50 Hz, while the remainder uses 1500 Vdc. The ac railroad network, which is the one of concern here, encompasses northern, northwestern and eastern France. The state-owned utility company, the Electricite de France (EDF), operates the 3-phase, 50 Hz national power grid and supplies all ac and dc electrified lines. A map showing the railroad network is given in Fig. 4.1. Table 4-1 presents data on the extent of French railroad electrification as of 1977.

As is always the case with 25 kV single-phase ac power, when the power demands encountered on most of the main lines have to be met, the length of the power supply sectors is restricted by the voltage drops observed at the pantograph on the cars. The 25 kV levels on the catenaries limit the distance between two adjacent substations to a range of 41.8 to 66.5 km.[4.2]

Additional information concerning the electrification existing in France is provided in Fig. 4.2 which shows where high voltage supplies from EDF is provided along the route of the new high-speed line (Paris to Lyon).

4.1 Source of Electric Power

The 25 kV substations of the SNCF are fed from the 63 kV, 90 kV and 220 kV 3-phase networks of the EDF. The SNCF has no 25 kV 50 Hz installations of its own for power generation and distribution.

Table 4-1

Extent of Electrification in France as of 1977. (Ref. 4.4)

Country, Railway, and Lines Electrified	Length Electrified: Route Km.	Length Electrified: All Track Km.	Voltage	System of Electrification	Conductor	Year Electrified
France—						
National Railways—						
Eastern and Northern Railway Systems						
North-eastern main line and branch-lines and lines in coal and iron ore areas	910	—	25,000	1/50	O H	1954-1964
Paris-(Est. Stn.)-Bale-Epernay - Charleville - Nancy - Dijon - Mulhouse - Dole and branch-lines and Paris (Est.) suburban Lines	1,382	..	25,000	1/50	O H	1956-1970
Northern railway system						
Paris (Nord Stn.)-Lille-Dunkerque - Aulnoye - Feignies - Jeumont - Collieries, and branch-lines	722	..	25,000	1/50	O H	1957-1964
Paris (Nord) suburban lines-Paris (Nord Stn.)-Verberie and branches. And outer circular (freight) line	250 5	..	25,000 1,500	1/50 D.C.	O H O H	1958-1970 1958-1970
Western Railway System						
Paris Western suburban lines	11 10 76	.. .. ..	1,500 25,000 750	D.C. 1/50 D.C.	O H O H 3 R	1972 1900-1936
Paris (St-Lazare Stn.)-Le Havre and branches	336	..	25,000	1/50	O H	1966-1969
Paris (Montparnasse Stn.)-Le Mans	213	..	1,500	D.C.	O H	1937
Le Mans-Rennes	162	..	25,000	1/50	O H	1964-1965
South Western Railway System						
Paris (Austerlitz Stn.)-Bordeaux - Irun and branches - Paris - Toulouse-Dax and lines in the Pyrenees-Toulouse-Sete	2,510	..	1,500	D.C.	O H	1910-1943
Paris Southern suburban lines	54	..	1,500	D.C.	O H	1939-1947
South Eastern Railway System						
Beziers-Neussargues	280	..	1,500	D.C.	O H	1931-1932
Paris (Lyon Stn.)-Lyon-Marseille - Lyon - St. Etienne and branches-Dijon-Bourg. Sete-Nimes Paris (Lyon) suburban lines	1,345	..	1,500	D.C.	O H	1949-1970
Lines in the Alps and Savoie-Culoz - Modane - Lyon - Culoz - Macon - Amberieu - Culoz to Swiss border	397	..	1,500	D.C.	O H	1953-1957
Villefranche La Tour de Carol	*63	..	850	D.C.	3 R	1910-1927
St - Gervais - les - Bains - Vallorcine	*34	..	600	D.C.	3 R	1901-1908
Aix-les-Bains-La Roche-sur-Foron and lines in Savoie	214	..	25.000	1/50	O H	1950-1954-71
Dole-Vallorbe-Pontarlier	117	..	25,000	1/50	O H	1958
Marseille-Vintimille	269	..	25,000	1/50	O H	1965-1969
	9,360	18,565				
Paris Metro (RATP)	172	..	750	D.C.	3 R	..
Réseau Express Régional (RATP)	60	..	1,500	D.C.	O H	..
Total	9,557	..	..	..	..	..

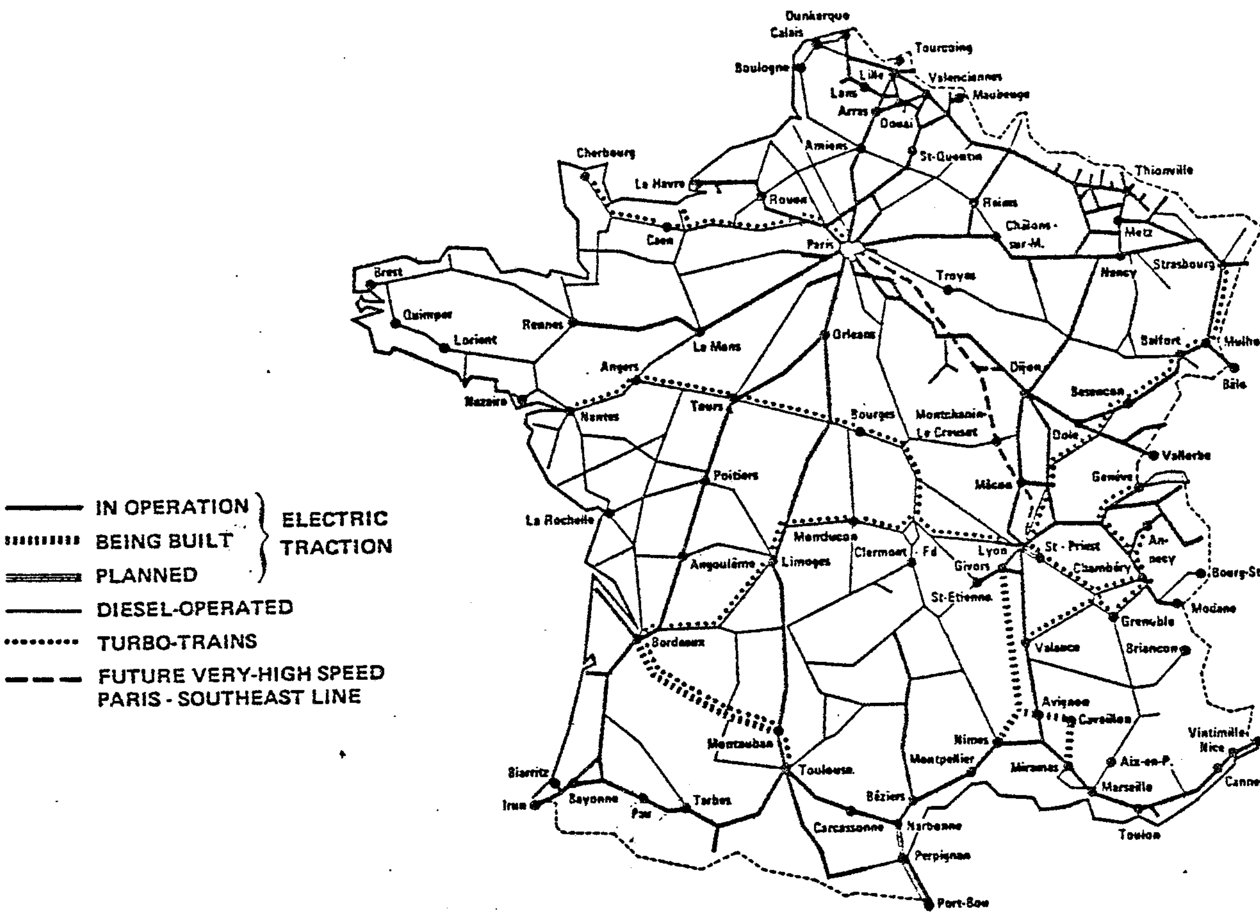


Fig. 4.1 Railroad Network of the SNCF (1975). (Ref. 4.1)

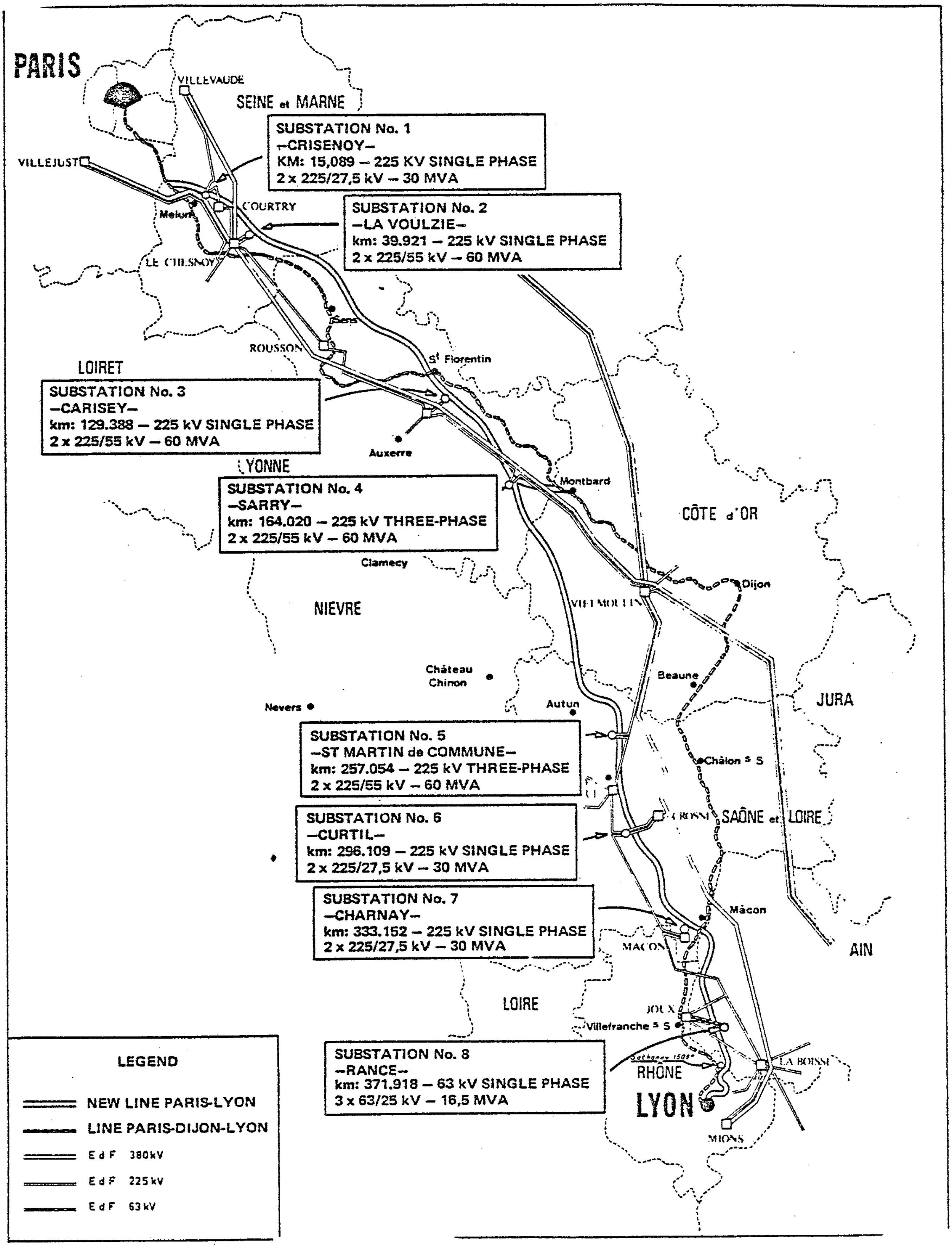


Fig. 4. 2 High Voltage Supply of the New Highspeed Line, (Ref. 4. 3)

Due to the unsymmetric load which the single-phase substations exert on the 3-phase network, certain operational difficulties were experienced at the beginning of electrification. To overcome them it was deemed necessary to use Scott transformers. Today, however, the 3-phase network of the EDF is so powerful that it is possible to connect up to four adjacent substations to the same phase of the 3-phase system without unbalancing the system by an unacceptable amount.

The feeder running from an EDF supply to an SNCF substation is a single-phase dual line. Equipment is fully duplicated to improve reliability and ensure continuity of power supply to the SNCF (a fail-safe philosophy). One of the twin lines is used for normal operation and the other is a standby reserve (Figs. 4.3 and 4.4) and is used only when maintenance work is underway on the primary feeder, or else in case of equipment failure. The circuitry is somewhat simplified when the SNCF substation is adjacent to a supply point of the National Electric Grid of the EDF. Feeders leading to the less important SNCF substations are not always duplicated, since the SNCF has found from experience that the feeder lines are very dependable and practically never fail. The feeder lines between the EDF grid and the SNCF substations are usually quite short; frequently the interconnecting EDF and SNCF points are adjacent. Only in rare instances are feeder lines as long as 10 km ever necessary.[4.1]

In order to handle any emergency, the EDF has asked the SNCF to be able to switch-over very rapidly between phases of the National Power Grid to which SNCF is connected. Groups of several substations, particularly those where the 220 kV line can be cut-off by

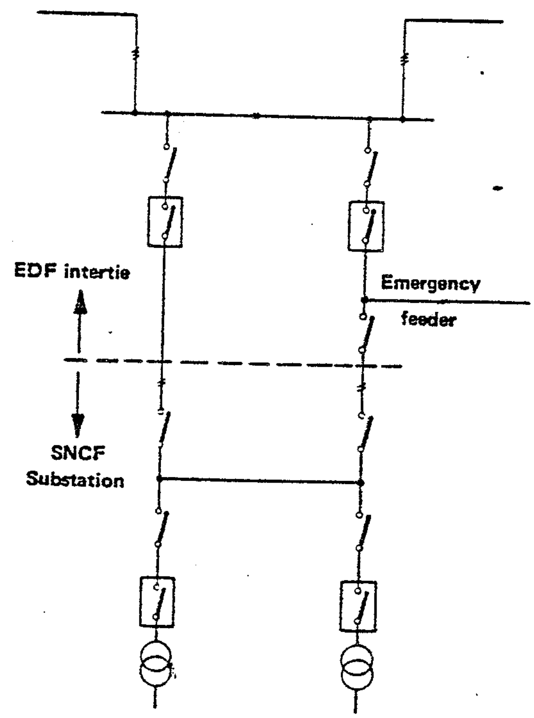


Fig. 4.3 Feeding of the SNCF 25 kV Single-Phase Substations from the Three-Phase National Grid of the EDF. (Ref. 4.1)

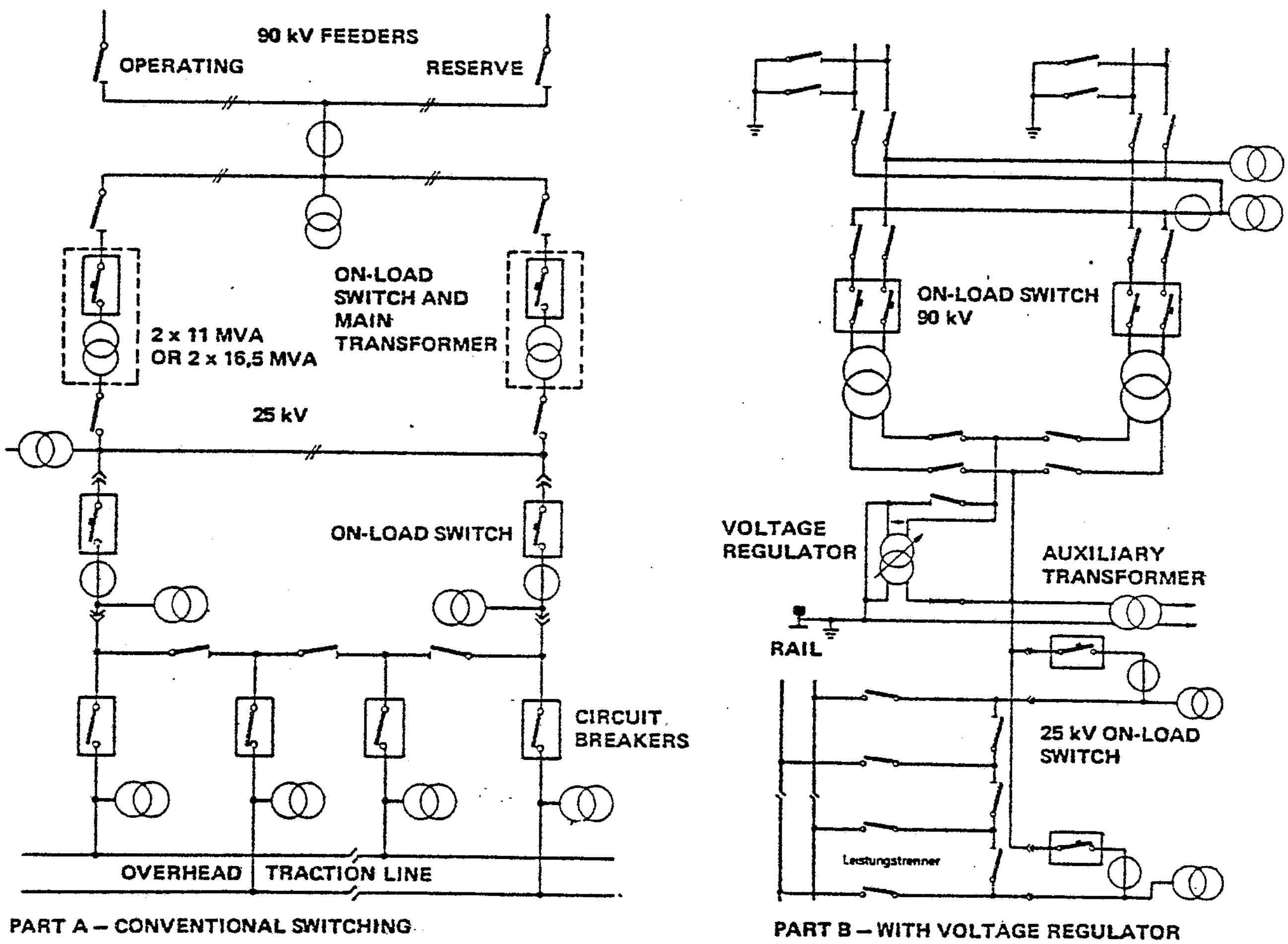


Fig. 4.4 Typical Switching Diagrams of the 25 kV Substations. (Ref. 4.1)

disconnecting switches, will be equipped with special disconnecting switches, protected by 3-phase 220 kV circuit breakers, enabling the SNCF to switch-over to other phases of the 3-phase supply by remote control.[4.3]

The circuit of a regular substation is depicted in Fig. 4.4, Part A. Primary and reserve circuits are each carried over a cut-off switch to a pair of bus-bars. One of these is connected through a current transformer to a third bus-bar. The bus-bars are connected to the power transformers via cutoff switches and power circuit breakers. The current and potential transformers referred to are used for protection and measurement.

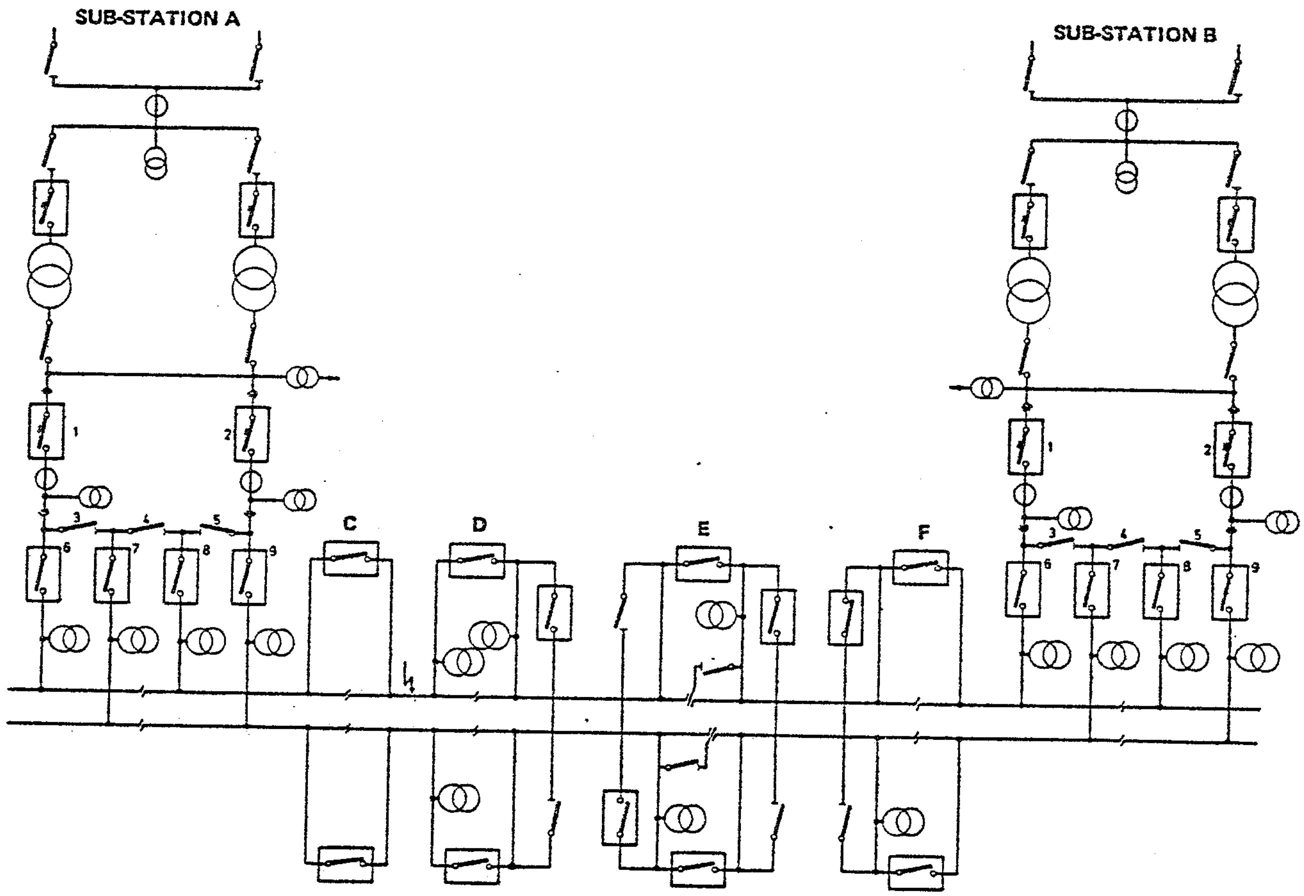
Since the SNCF draws its power from the EDF and must pay the EDF for reactive power within certain limits, the SNCF endeavors to avoid the flow of power over the overhead catenary from substation to substation. Moreover, such a power flow would increase losses and would unnecessarily load the overhead catenary line. For these reasons, the SNCF continuously adjusts the voltage of the catenary wire at many of its substations. The relevant circuit diagram is shown in Fig. 4.4, Part B. For the purpose of regulation, an adjustable voltage is added to the contact wire voltage. This adjustable voltage is derived from a device connected to the rail side of the contact wire. This regulating device consists of a tapped transformer, an on-load tap changer and a control circuit. The use of voltage regulation is regarded as economical, especially in view of the low traction line losses and the reduction of inductive load transfer between substations via the catenary achieved with this technique.[4.1]

The SNCF decided to install load regulators on the transformers of substations supplied at 220 kV after two years of satisfactory experience was obtained with this feature at similar substations in the Paris region. The regulator has a long response time and is not influenced by a single train, which draws only a small fraction of the nominal power of the transformer. However, it is actuated at the time of a phase break crossing by a cumulative overload. It also compensates for variations of the high voltage supplied by EDF. Thus, by raising the line voltage when a high current is drawn, the regulator enables the substations to be set farther apart, or it allows the system to meet a high power demand.[4.3]

Bearing in mind the variable density of rail traffic, the transformers are specially designed for periodic overloads and frequent short circuits. They have been standardized in two sizes of rated power: 11 MVA and 16.4 MVA. Recently, in the Paris area 30 MVA and 60 MVA transformers, fed at 220 kV by the EDF, have been installed on the new high-speed line.[4.1]

4.2 Method of Supplying Catenary

The basic circuit of a double-track section between two substations is presented in Fig. 4.5. The overhead line is fed from the substation through a total of one or two on-load circuit breakers and one cut-off switch per feeder. Under this arrangement it is possible in the event of the failure of one circuit breaker to supply all four feeders through the other circuit breaker. At the substation the overhead traction lines of the two tracks can be separated by means of a sectioning cut-off switch, which is specifically provided for use



C – SECTIONING POINT
D – SECTIONING AND IN-PARALLEL CONNECTING POINT
E – COUPLING POINT
F – SECTIONING AND IN-PARALLEL CONNECTING POINT

Fig. 4.5 Switching Diagram of the 25 kV Overhead Traction Network Between Two Substations. (Ref. 4.1) during breakdowns and maintenance work on the line. In the basic circuit (Fig. 4.5) the power circuit breakers 1 and 2, the cut-off switches 3 and 5 as well as the load cut-off switches 6-9 of both substations A and B are closed, but the sectioning cut-off switch 4 is open. Likewise all isolating switches and load cut-off switches located at sectioning points, sectioning and in parallel connecting points as well as paralleling points are closed.

The reason that the SNCF uses single-phase substations operating at the same phase is to minimize the number of phase breaks while operating over parallel tracks. The Scott configuration is not used because it requires that a phase break be installed at each substation. The SNCF approach reduces the per unit voltage drops in the catenaries, thereby increasing the spacing of the substations.

For ecological as well as technical and economical reasons, the SNCF have tried, whenever possible, to place the substations as close as possible to the points of the highest power capability in the EDF power grid. Some of the intervals between substations, particularly between some of the substations on the new high-speed line are very long (Fig. 4.6). In fact, some are close to 90 km. Such distances do not enable trains to be properly supplied if their peak power reaches 14,000 kW. The SNCF has therefore decided to use a device on the new high-speed line conceived by an American in 1913, and used by the Japanese on the New Sanyo Line, which is the following (Fig. 4.6): a feeder, hung on the same supports as the catenary line, is kept at a voltage of an opposite phase with that of the catenary line (hence its designation as feeder "-25kV"). Every

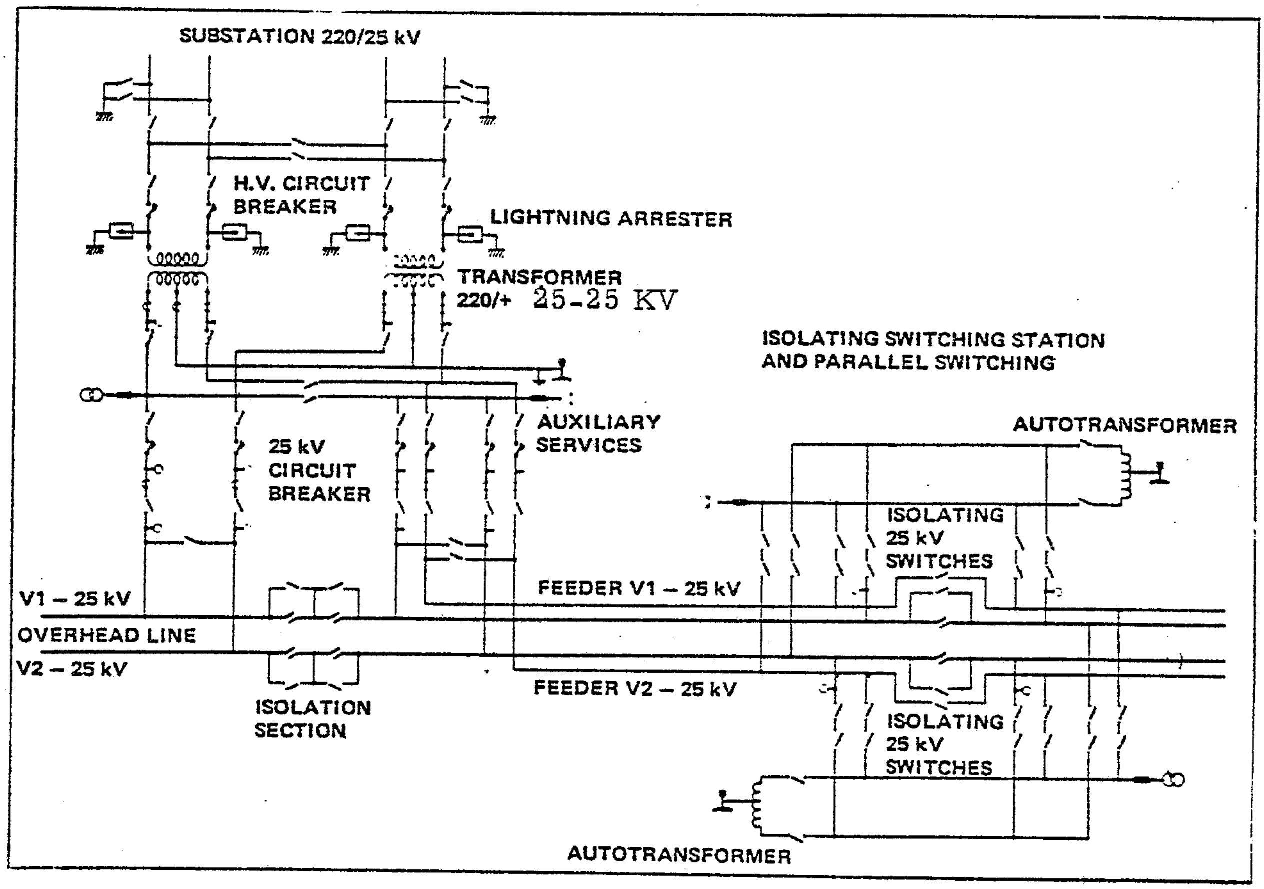


Fig. 4.6 Autotransformer Supply Arrangement Used on the New High-Speed Line. (Ref. 4.3)

15 km an autotransformer is provided, whose center tap is connected to the rail; one terminal to the feeder, and the other to the catenary trolley wire. This configuration is equivalent to a single-phase 50 kV power line. Thus the service range of the substation is greatly lengthened; in effect it is practically doubled.[4.3]

Since the SNCF is contractually obligated to pay the EDF for inductive power within certain limits, some substations are fitted with supplementary equipment to compensate for inductive power. This is principally the case for substations which carry a light load so that the ratio of active to idle power is especially unfavorable, due to a steady level of idle power drawn by the transformers. Compensation of the order of several hundreds of kVA is achieved by using capacitors, so that on the average the power factor should not decline to the point where much idle power must be purchased.[4.1]

The 220 kV transformers for the Paris region of the high-speed line are equipped with Jansen regulators to control the catenary voltage. The autotransformers used on the new line require a very low reactance.

The truly new features of the new high-speed line are the 25 kV circuit breakers and switches. The presently-used circuit breakers are derived from those operating at 63 kV. While their nominal current rating and breaking capacity are sufficient. their durability in service is low. On a high voltage grid, the number of switching actions under load typically does not exceed a few per year; on a 25 kV catenary line, this number is 10-to-20 times higher. The contact points are therefore used up extremely fast, and must be replaced often. The new sulfur hexafluoride circuit breaker is far more durable and requires less maintenance than the present unit.[4.3]

4.3 Track Sectioning Details

Since the utility generates and transmits 3-phase power and the catenary uses single-phase power, the individual SNCF substations are necessarily connected to different phases of the network. Thus, phase breaks in the catenary are necessary. This complicates the operation of electric trains.[4.1]

The number of phase breaks on the new high speed line is kept as small as possible, since crossing them interrupts the tractive effort for more than 30 seconds, and thus impedes the movement of the trains.[4.3] In the overhead lines, switches are installed at 10 km to 15 km intervals. These are either "sous-sectionnements," i.e., sectioning and in parallel connecting points; or "sectionnements et mise en parallele," corresponding to the conventional paralleling points (Fig. 4.5). The sectioning points are equipped with only one sectioning device per track, which is bridged by an on-load circuit breaker. The sectioning and in parallel connecting points also make it possible to connect two tracks in parallel. Finally, only one paralleling point is installed between two substations. It is equipped, in addition to the two section cut-off switches associated with respective neutral sections of the trolley wire, with a further on-load switch for connecting the two tracks in parallel. This makes it possible to operate, on occasions, two sections of the same line in parallel.

In normal operation, coupling points between substations of the same phase are closed. However, under special circumstances, i.e., in suburban traffic during the period of heaviest load, or in the event of a "travelling" load due to heavy, fast trains in the star-shaped network, the coupling points are thrown open. This is done to avoid situations in which, due to a voltage difference between two neighboring stations, costs accrue to the SNCF because of the transfer of active and idle power over the overhead contact line, especially in the case of substations without voltage regulation.[4.1]

4.4 Summary

In France 25 kV 50 Hz power is supplied to 4500 route km (1977) of electrified railroad from the utility network at 63 kV, 90 kV, and 220 kV. Most substations contain a spare transformer and are spaced between 41 and 67 km apart. The substations are connected through the catenary where additional power is needed, and voltage-regulated transformers at substations are used to minimize unnecessary current for this condition. Reactive compensation is provided at some substations to increase the substation power factor. Catenary sectioning points are spaced every 10-15 km, and three different schemes for sectioning the catenary are used. The new high-speed line uses auto-transformers spaced every 15 km to allow greater substation spacing and to reduce interference with communications circuits.

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5.0 UNION OF SOVIET SOCIALIST REPUBLICS

Electrification moved ahead rapidly following approval by the Council of Ministers of the Electrification Master Plan in 1956; during the next five years, lines totalling 8,500 route km were equipped. At present (1977) some 38,900 route km or about a quarter of the SZD network is electrified to haul 50 percent of the freight traffic in the country. A map of the electrification in the USSR is shown in Fig. 5.1. The basic advantages of electric traction foreseen sixty years ago in the USSR hold good to the present day, namely economy of fuel and increased line capacity, accompanied by increased utilization of motive power.[5.1]

All new electrification will be at 25 kV 50 Hz, except for extension of existing 3 kV dc systems, to avoid changing catenaries. Other voltages (e.g., 10 kV 50 Hz) are used for special applications such as mine hauls. The extent of the electrification at 25 kV and 3 kV is shown in Table 5-1. Voltage limits on the 25 kV 50 Hz main lines are between 21.0 kV and 29.0 kV while limits on secondary lines are 19.0 kV to 29.0 kV.[5.2] AC electrification is favored because the interval between substations can be increased from 24 km for dc lines to 44 km for ac, and the equipment is naturally less complex without the need for rectifiers. Furthermore, power losses in the transmission lines and overhead wires with ac electrification are generally reduced by a third to 3 or 4 percent of the total power used.[5.3] Not all lines are powered by a single type of current. On some lines, some sections operate on ac and other sections on dc, necessitating either changing of electric locomotives or use of special wayside equipment to change the type of power supplied.[5.2]

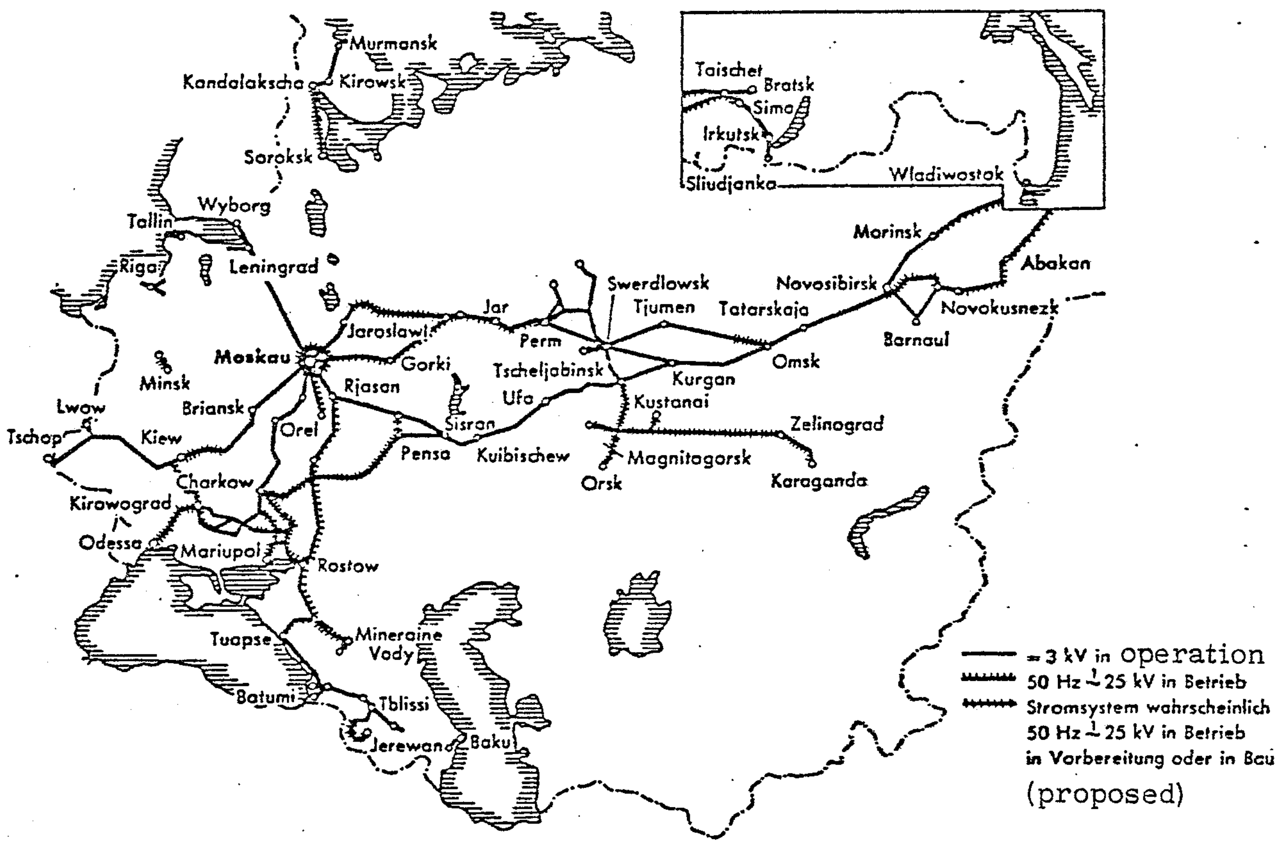

Fig. 5.1 Map Showing the Electrification in the USSR as of 1971. (Ref. 5.4)

Table 5-1

Extent of Electrification in the USSR as of 1977. (Ref. 5.5)

Country, Railway, and Lines Electrified	Length Electrified		Voltage	System of Electrification	Conductor	Year Electrified
	Route Km.	Track Km.				
Union of Soviet Socialist Republics-						
. . . .	24,085	..	3,000	D.C.	O H	1931
. . . .	14,923	..	25,000	1/50	O H	1955
Total . . .	38,923	..	..	..	..	..

5.1 Source of Electric Power

Power for the railroads is supplied through the same transmission lines that supply other consumers. Thus, the railroads are only a part of the general electrification of a region. In some case, railroad power substations are fed by regional substations. More than 50 percent of the power produced by the regional substations is applied to noncatenary uses.

Fig. 5.2 shows a large railroad substation. This substation which not only feeds the railroad, but also feeds single-phase power to the surrounding region, is a completely dual-feed system. It includes two dual 110 kV feeders, two 38.5 MVA, 110 kV/27.5 kV, 3-phase transformers connected wye-to-delta and small 27.5 kV to 10 kV auxiliary power transformers. For substations requiring other capacities, transformers of the appropriate ratings are supplied.[5.2]

One corner of the delta at each substation is grounded to the rail; the other two corners are connected to the adjacent catenary sections. Hence, the substations are loaded on two phases when the catenaries are equally loaded. Static capacitors are used at the substations to improve the power factor, and their effect is to increase it from 0.82 - 0.85 up to 0.92 - 0.95. As shown in Fig. 5.2, reactors are installed in series with the capacitors to suppress the high harmonics generated by mercury arc rectifiers on the locomotives.[5.3]

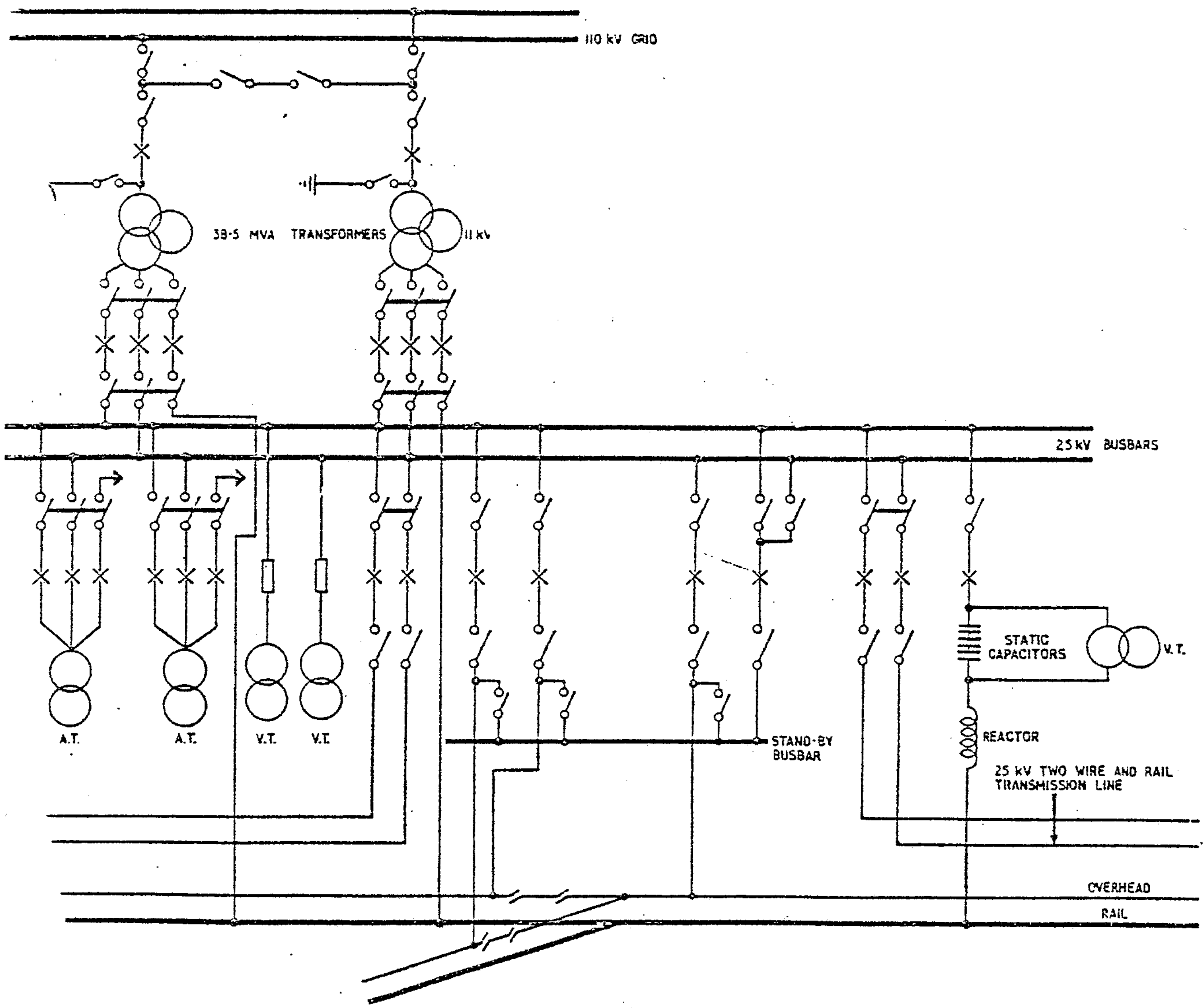

Fig. 5.2 . Schematic Diagram of a Typical AC/Substation with 25 kV Transmission Lines to Serve Lineside Consumers. (Ref. 5.3).

5.2 Method of Supply Catenary

Catenary in this area is fed from a 3-phase delta secondary transformer with two phases going out from each substation. Fig. 5.3 shows the schematic diagram of the feeding system.

So that substations can be located as far apart as possible without excessive voltage drop on the overhead lines, phase breaks are placed at the substations and each section of line between substations is fed from both ends at the same phase, as shown in Fig. 5.3. The allocation of the phases to supply the catenary and the local single-phase load over a considerable length of track is shown in Fig. 5.4.

Booster transformers are used only where needed, in areas with high telecommunications interference. Their purpose is to limit return current flowing through an earth path by forcing most of the current through the running rails. They are spaced 4 to 5 km apart. Fig. 5.5 shows a diagram of a booster transformer circuit. The transformer has a one-to-one ratio, with 88 turns on both primary and secondary.

Plans are being made for the introduction of a 2 x 25 kV ac system (Japanese system) in which the 25 kV contact wire is fed from an autotransformer with a regulator-controlled center tap. The center tap is connected to the rail; the other end of the autotransformer is connected to a 25 kV feeder. (See Fig. 6.5 under Japan). In this system, the electric locomotive is of the 25 kV class. The system allows for compensation of voltage drops on the line.[5.2]

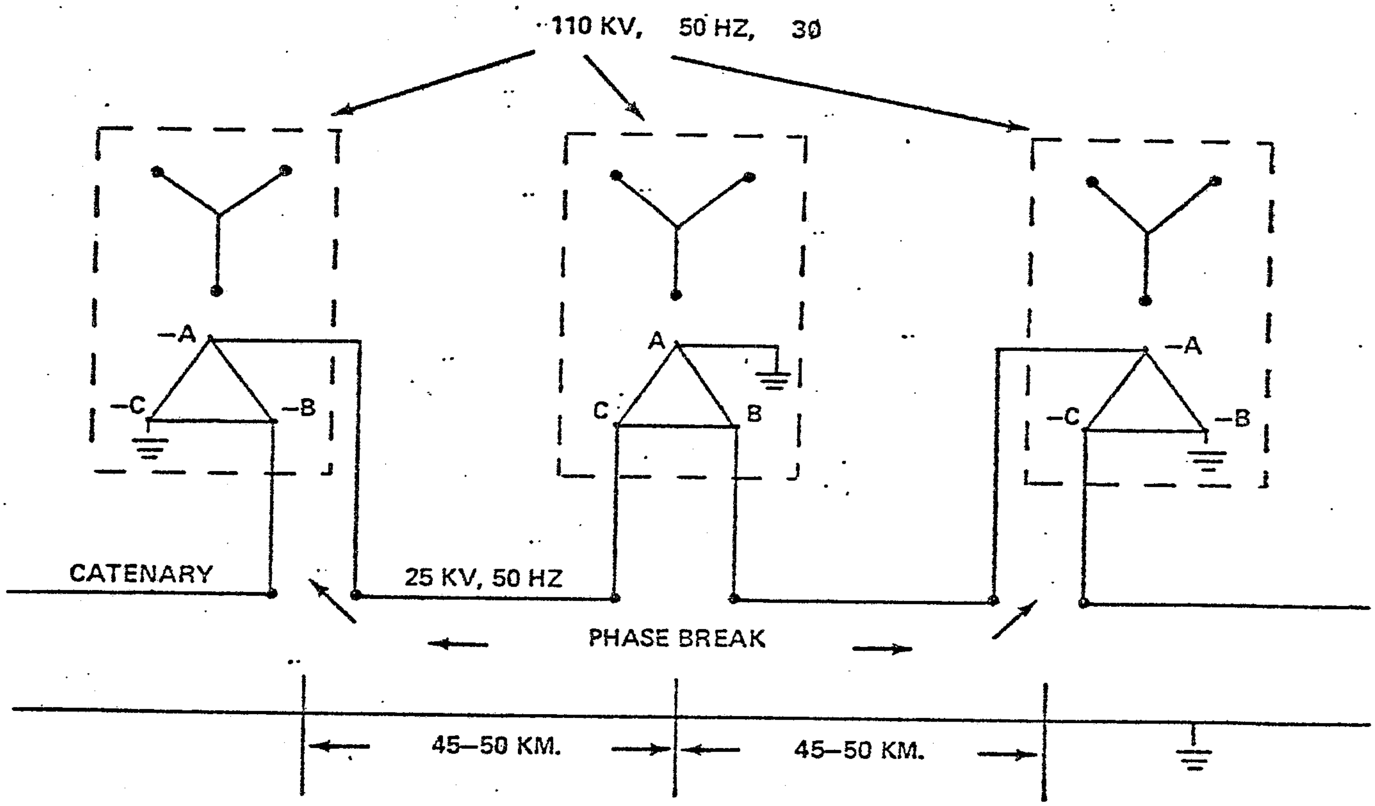

Fig. 5.3 Schematic Diagram of the 25 kV, 50 Hz Line. (Ref. 5.2)

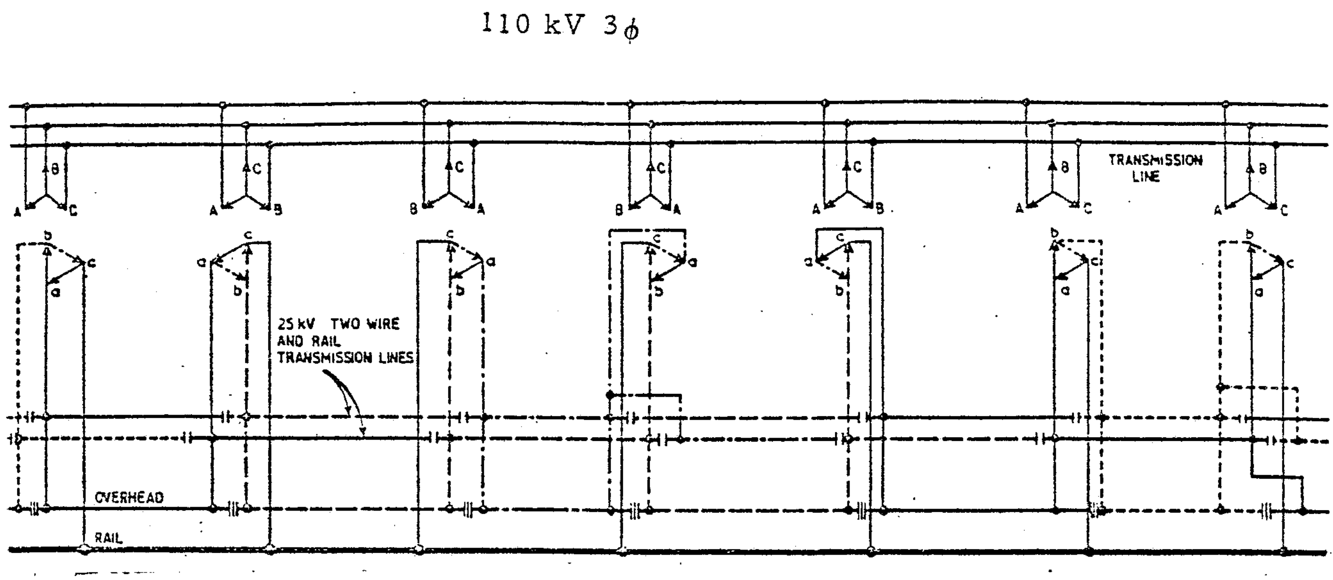

Fig. 5.4 Phase Distribution along a Typical AC Route with a 25 kV Supply to Lineside Consumers. (Ref. 5.3)

Legend: —|||— Phase Break


Wye-Delta Transformer

Note: Lettering on the transformers describes the phase relationship between the primary and secondary windings.

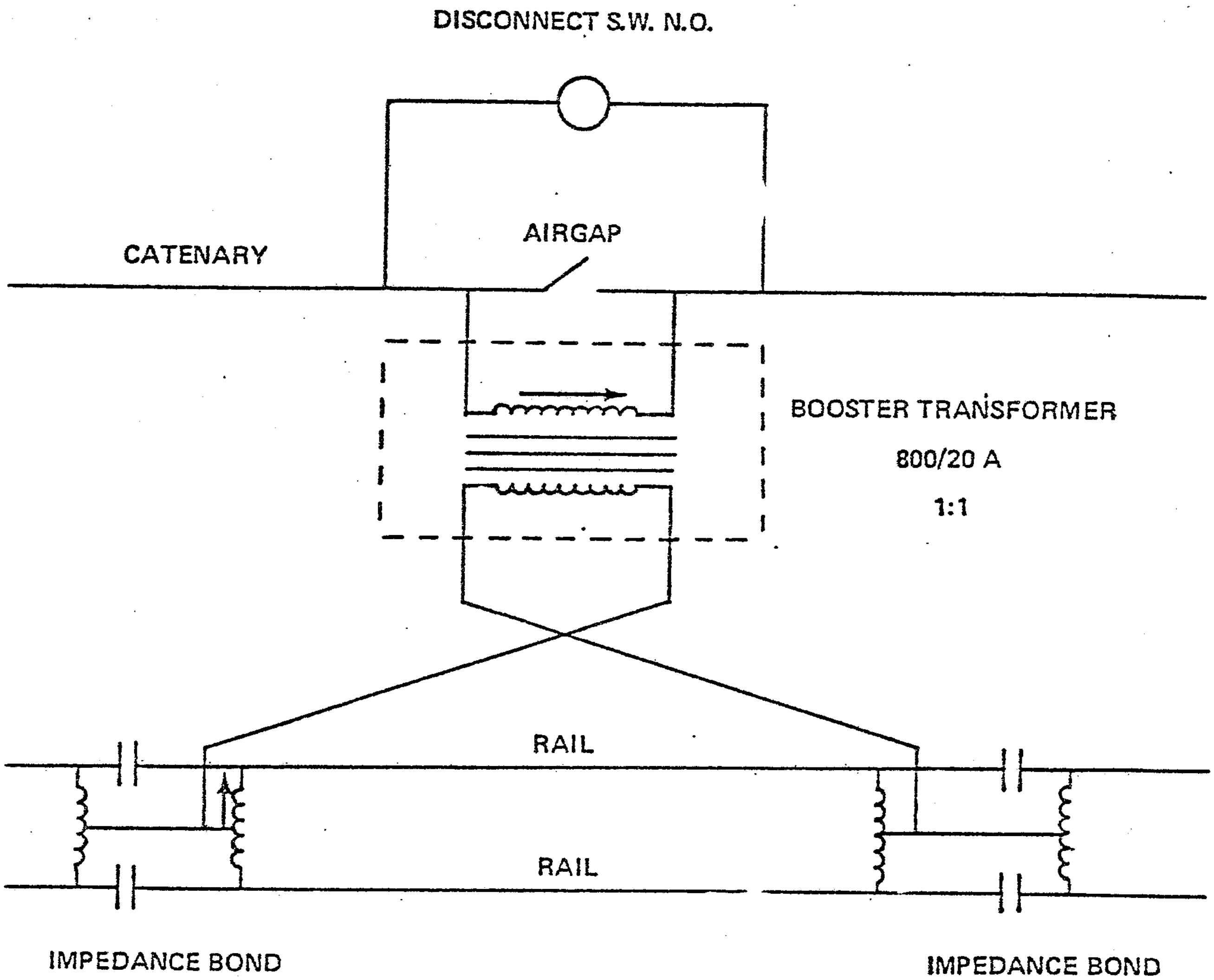

Fig. 5.5 Diagram of the Booster Transformer Circuit.
(Drawn as in the Ref. 5.2)

5.3 Track Sectioning Details

Where ac and dc rail lines meet, the transfer of motive power generally has been carried out by switching the wayside power source feeding the overhead line directly from ac to dc, or vice versa. A special changeover switch has been devised for this purpose. At these junction stations the route relay interlocking is extended to include the switching of the overhead traction supply, so that a locomotive cannot be driven across an overlap between different voltages without disobeying signals.[5.3] No changes to the locomotive are needed with this system which allows a quicker throughput of trains.

5.4 Summary

In the USSR 14,900 route-km (1977) of electrified track is supplied by 25 kV 50 Hz power taken from the utility 110 kV network. Three-phase transformers are used at substations. Two of these phases are used to end-feed the catenary, with the unused phase supplying local loads. Substations are spaced 45-50 km apart and contain capacitors for reactive compensation and filters to reduce harmonics. Booster transformers are used where needed to reduce interference. Special system changeover wayside switches are located at some locations where ac and dc systems meet so that locomotives can crossover and operate in both zones. Plans are being made to use the autotransformer system as is used in France and Japan.

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6.0 JAPAN

DC electrification had predominated up to 1955 in Japan. It has been superseded by an electrification, which is now more preferred in recent electrification projects of the Japanese National Railways (JNR). As shown in Table 6-1, as of 1977 Japan has 13,700 route km of electrified railroads.

Under ac electrification in Japan, the New Tokaido Line (NTL) is supplied at 25 kV, single-phase and the conventional JNR lines at 20 kV, single-phase, the frequency being 50 or 60 Hz. Power frequencies of 50 and 60 Hz are both used for railroad electrification, since power is supplied at 50 Hz in the eastern section of Japan near Tokyo while 60 Hz is used in the western areas.[6.1] A map of the new electrification is shown in Fig. 6.1.

For a 25 kV railroad supply voltage it was found that the maximum feeding distance is about 10 km. Based on this, the distance between substations was fixed at about 20 km.[6.2] However a new approach for supplying power to the catenary was implemented in Japan. This system places 50 kV across autotransformers along the railroad with a center tap attached to the running rails. This arrangement allows the substation spacing to be increased to about 50 km.

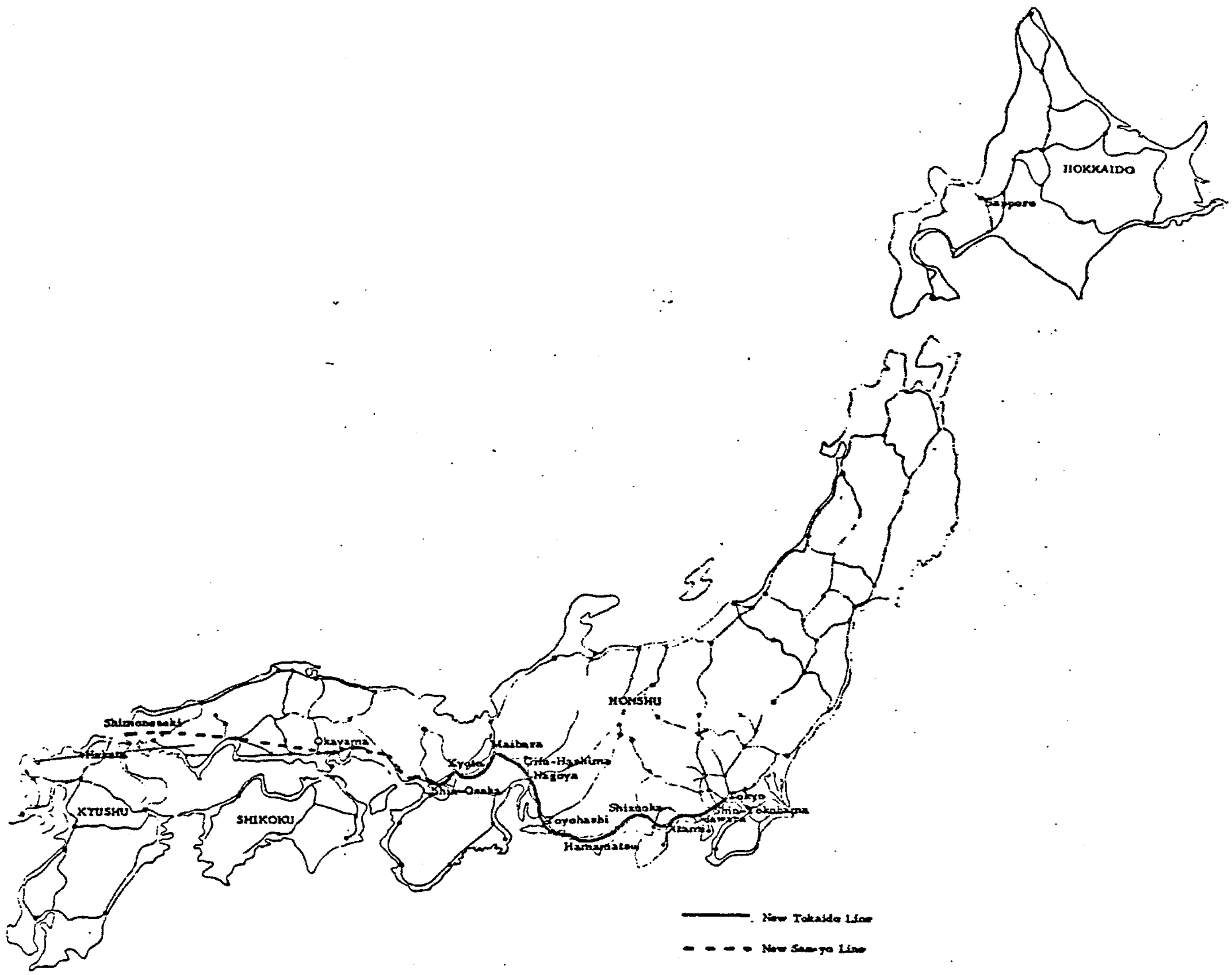
6.1 Source of Electric Power

Fig. 6.2 is a one-line diagram of an ac traction substation, which consists of the power-receiving (supply) circuit, the transformer circuit, the feeder circuit, and the high-tension power-distributing

Table 6-1

Extent of Electrification in Japan as of 1977. (Ref. 6. 6)

Country, Railway, and Lines Electrified	Length Electrified		Voltage	System of Electrification	Conductor	Year Electrified
	Route Km.	All Track Km.				
Japan—						
Japanese National Railways—						
Tokaido Line	1,404	4,578	1,500	D.C.	O H	1909-76
	6		20,000	1/60		
Hokuriku Line	43	1,118	1,500	D.C.	O H	1943-69
	319		20,000	1/60		
Chuo Line	601	1,343	1,500	D.C.	O H	1906-73
San-yo Line	791	2,325	1,500	D.C.	O H	1934-70
	6		20,000	1/60		
Kansai Line	141	217	1,500	D.C.	O H	1932-73
Tohoku Line	712	5,401	1,500	D.C.	O H	1909-68
	997		20,000	1/50		
Banetsu Line	82	131	20,000	1/50	O H	1967
Ou Line	493	1,117	20,000	1/50	O H	1949-75
Uetsu Line	85	645	1,500	D.C.	O H	1972
	212		20,000	1/50		
Shinetsu Line	331	985	1,500	D.C.	O H	1911-69
Sobu Line	484	1,093	1,500	D.C.	O H	1932-74
Kagoshima Line	403	1,033	20.000	1/60	O H	1961-75
Nippo Line	343	680	20,000	1/60	O H	1966-74
Hakodate Line	171	653	20,000	1/50	O H	1968-69
New Tokaido Line	553	1,330	25,000	1/60	O H	1964
New San-yo Line	624	1,374	25,000	1/60	O H	1972-75
Total state-owned	8,805	23,963				
Privately-owned railways—						
Various undertakings	3,618	7,306	1,500	D.C.	O H	At various dates
	134	174	750	D.C.	O H	
	1,023	1,773	600	D.C.	O H	
	74	180	750	D.C.	3 R	
	80	189	600	D.C.	3 R	
	8	9	1,500	D.C.	G R	
	25	51	750	D.C.	G R	
	6	10	600	D.C.	G R	
Total, privately-owned railways	4,968	9,752	..	..	..	..
Total, all lines	13,773	33,715	..	..	..	..



Route map.

Fig. 6.1 Route Map of Japan's New Electrification Railways. (Ref. 6.2) (auxiliary) circuit. The power-receiving circuit and the high-tension power-distributing circuit are not too different from those of a dc substation. Since the ac substation capacity is generally larger than the dc substation capacity, the former being 20-200 MVA, the receiving circuit is directly connected to a large power system ranging from one rated at 60/70 kV to an extra-high tension one rated at 270 kV.[6.1] The electrification facilities of the Shinkansen between Shin-Osaka and Hakata were designed presuming that 16-car EMU trains would be operated with five-minute headway at 250 km/h in the future. Hence, the substations are supplied from high-capacity sources rated 275 kV or 220 kV.[6.3]

Of the total 515-km length of the NTL, about 140 km are located in the 50-Hz area (Tokyo side). Therefore, in order to maintain a 60 Hz frequency for the entire line, it was necessary to establish frequency-converter stations; two such stations have been built, at Tsunashima and Nishisagami. The output of the frequency-converter, 3-phase on both primary and secondary, is 60 MVA. From these frequency-converter stations power is supplied to six traction substations at 60 Hz through transmission lines. For the underground cables, a newly developed 70-kV grade aluminum-sheathed oil-filled cable has been used. In other areas, 60-Hz power is received directly from the various power companies through their non-JNR transmission lines.[6.2]

The transformer circuit of Fig. 6.2 serves to convert the three-phase power to two-phase power for railway traction. As shown in Fig. 6.3, a Scott connection or a modified Woodbridge connection transformer (App. A) is employed to produce two single-phase

SUPPLY FROM THE UTILITY

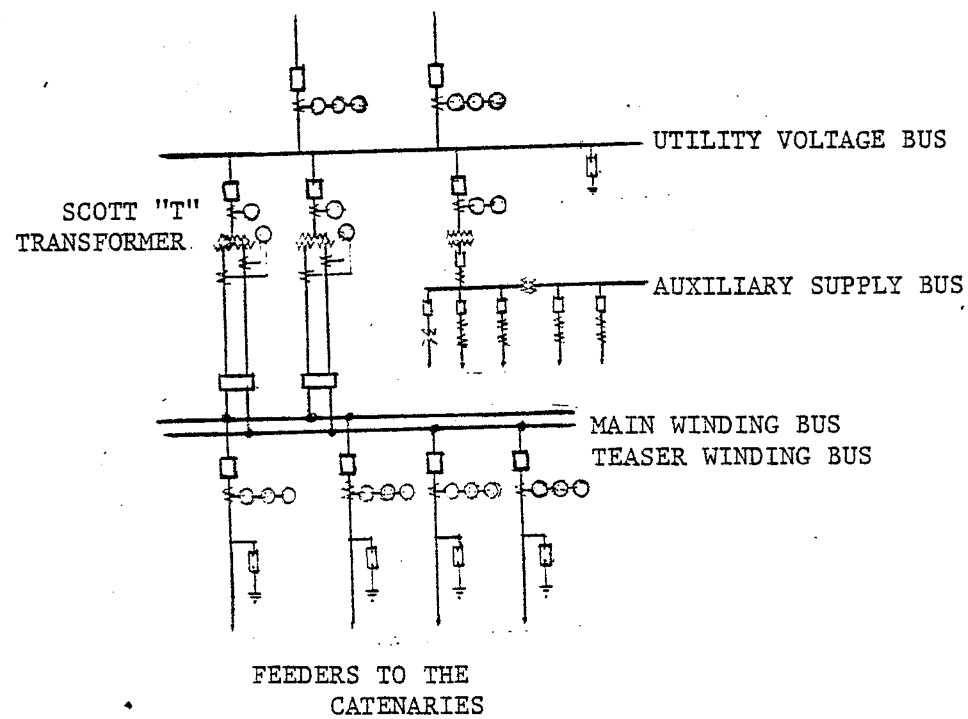


Fig. 6.2 Configuration of a Traction Substation with Scott "T" Transformers Used in Japan. (Ref. 6.1)

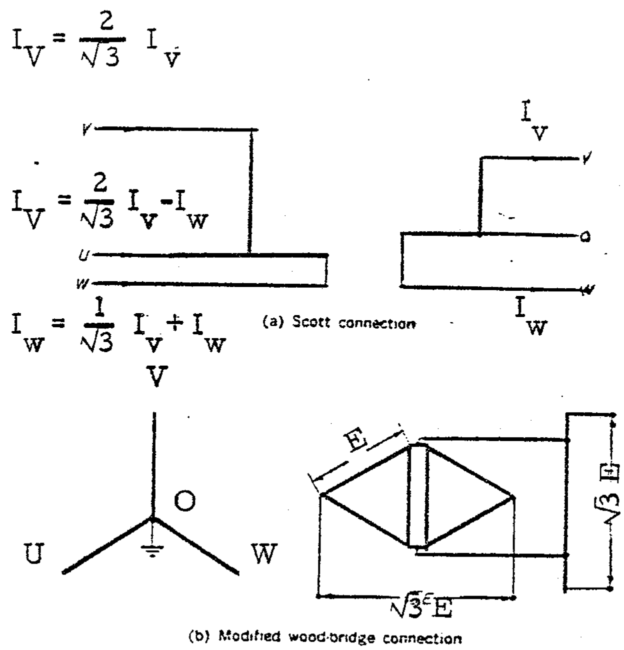


Fig. 6.3 Connections of Transformers:
(a) Scott, (b) Woodbridge. (Ref. 6.1)

voltages with a 90° phase difference, in order to reduce the effects of unbalanced loading on the three-phase power supply network. Use of such a modified Woodbridge connection is necessitated for a direct-grounded power supply like a 275 kV system, which requires a neutral point in the primary winding of a transformer.[6.1] The feeding transformer has a continuous 100 percent rating corresponding to one-hour maximum demand, and is capable of withstanding instantaneous maximum power of 200 percent under normal conditions, and instantaneous maximum power of 300 percent in case of emergency. Further, the percent impedance of the transformer has been suppressed to 4 percent to reduce voltage drop. The continuous rating of the transformers on the New Tokaido Line is 30 MVA.[6.2]

6.2 Method of Supplying Catenary

As was mentioned previously, the Scott connection or equivalent has been adopted for the feeding transformers. This was done to minimize unbalance in the 3-phase supply system and to avoid the trouble of trains having to notch off at the phase breaks between different phases. This problem was remedied on the NTL by using one phase for feeding power to the full length of the northbound tracks, and the second (90°) phase for feeding power to the full length of the southbound tracks. That is, there is no phase change at the phase breaks.[6.2]

Under ac electrification, to prevent inductive interference with communication lines and other facilities caused by the practice of shunting of the return current with the earth, the booster transformer (BT) system has been in use. The booster transformer is inserted between trolley wire rails and return feeder, as shown in Fig. 6.4, to force the current into the return feeder. Now a new autotransformer (AT) system, which increases the spacing between substations and renders the feeding more economical, has been developed. This system is adopted for the New Sanyo Line (between Shin-Osaka and Okayama). Fig. 6.5 is a schematic diagram of the AT system.[6.1]

The BT system with a return feeder as shown in Fig. 6.4 has been employed with the transformers installed at 1.4 km spacing near urban areas and at 3 km spacing in other areas. On the NTL, a very large current flows on the overhead contact wire, as compared with that of the conventional narrow-gauge system. There is a possibility of an arc being generated as the pantograph shoe passes over the dead section where the booster transformer is installed, and thus damaging the overhead contact wire or the pantographs. To avoid such occurrences, another section 25 m long has been additionally inserted, and a 10Ω resistor has been installed to suppress the generation of arc (Fig. 6.4). The resistor limits the current which is to be cut when the pantograph passes the section to about one-quarter of its former value.

Many of the section posts (gap breaker stations) and booster transformers on the NTL are distributed below the elevated track structures, of which the NTL has a great number. At such places, 30-kV grade butyl rubber cable is used for wiring. Silicon resin-formed insulators strengthened by high tracking-proof and wear-proof glass fiber have been employed both for the same and for different phases.[6.2]

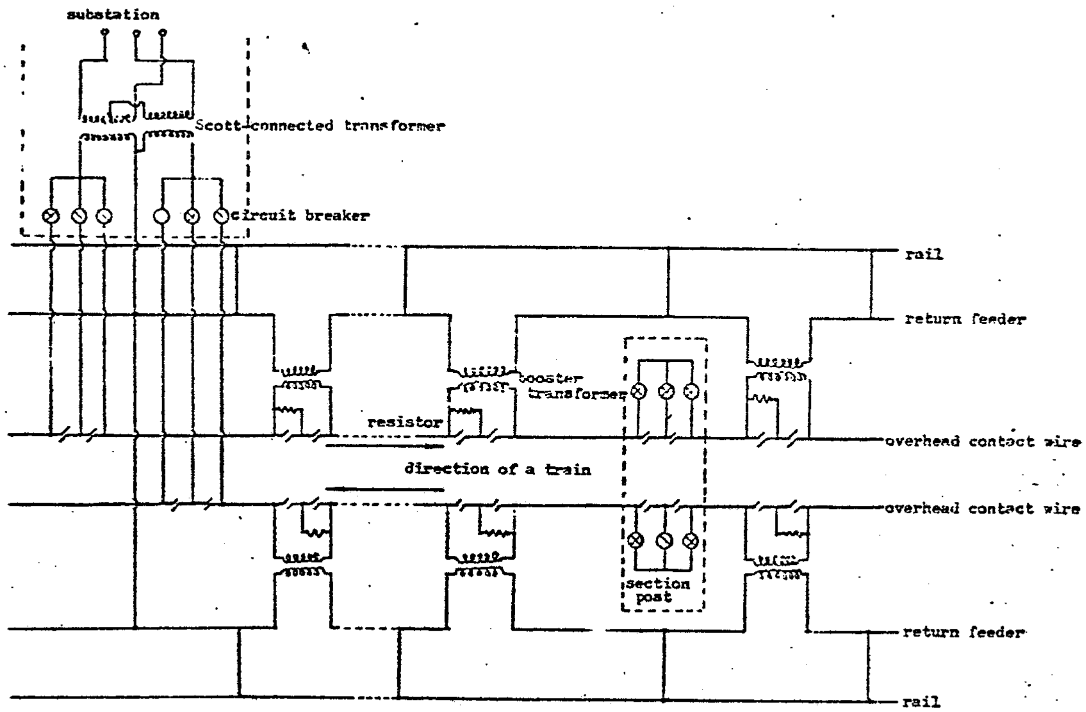


Fig. 6.4 Method of Installing Booster Transformers. (Ref. 6.2)

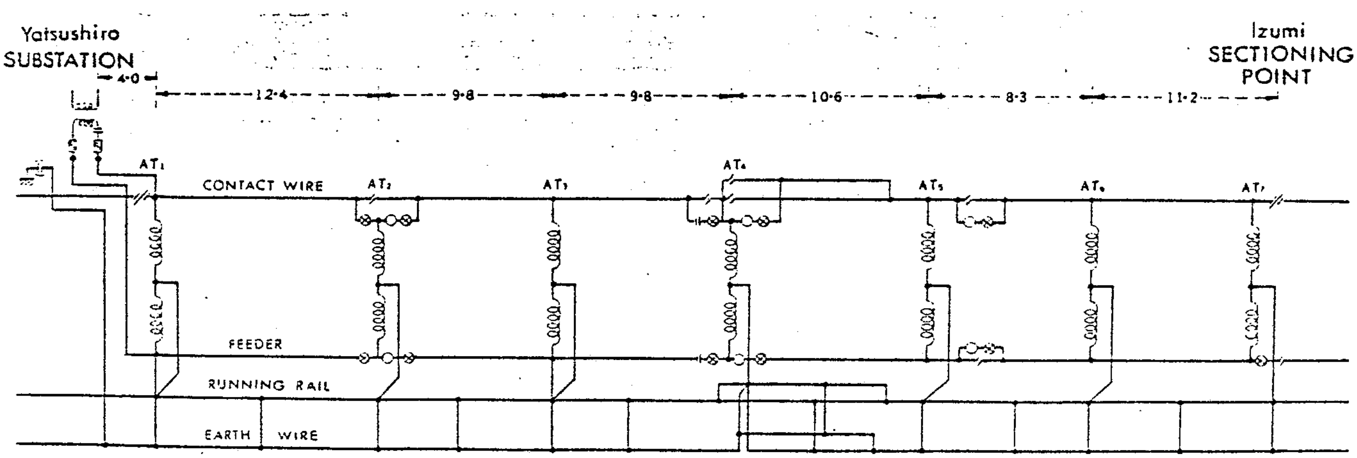


Fig. 6.5 Method of Feeding Contact Wire with Autotransformer System. (Ref. 6.4)

The AT feeding system is a system in which power is supplied to the electric vehicles from a feeding circuit using autotransformers. To allow through operation between the Tokyo-Shin-Osaka section (25 kV BT feeding system) and the Shin-Osaka-Hakata section, the feeding voltage was determined to be 50 kV and the contact line voltage to be 25 kV. The rated self-capacity of the autotransformers is standardized at 10 MVA.[6.3] JNR commenced detailed studies of AT feeding in 1966, and carried out tests on the Mito Line before finally adopting it between Yatsushiro and Kagoshima. Briefly, the tests confirmed that voltages induced in communications circuits were less than with booster transformers, and voltage drop was reduced as expected because the current in the contact and feeder wires is approximately half that drawn by the train. The Kagoshima Line was the first large-scale application in Japan of a feeding arrangement in which booster transformers are replaced by 2:1 autotransformers spaced at about 10-km intervals. This allows the output at the substation to be at double the catenary voltage, so that grid in-feed points can be more widely spaced for a given voltage drop.[6.4]

Autotransformer (AT) feeding has now been adopted as standard by JNR.[6.4] By introducing the AT feeding system, it was possible to build the substations at about 50 km intervals, 2.5 to 3 times further apart than the BT feeding system of the Tokyo-Shin-Osaka section. As shown in Fig. 6.2, the substations are of the two-unit system, each unit comprising 275 kV or 220 kV power receiving facilities and one set of 150 MVA feeding transformers. Normally, one unit is in service and the other in reserve. Since power is received from solidly-grounded super high-tension networks, the modified

Woodbridge transformer was developed for the railroad substations. (See Fig. 6.3.) Installation reliability is enhanced by providing reserves for feeding facilities [6.3] and by providing an earth wire which parallels the rails to give lightning protection to the overhead conductors. [6.4]

The BT system uses separate gap sections operated at reduced power to control or eliminate overhead arcing as train passes slowly under the gap. Under the AT system, these separate sections required on the trolley wire under the BT system are not needed, so a larger amount of power can be supplied. [6.1]

The advantages gained by the AT system over the BT system are summarized as follows:

(1) Distribution at twice system voltage results in increased substation spacing by a factor up to four.

(2) Elimination of arcing when pantographs would cross booster overlap spans, experienced with traction current of the order of 700 A or more.

(3) Additional impedance from booster transformers is eliminated.

Disadvantages of the AT system are:

(1) The return feeder supported on the towers requires the same insulation level as the overhead equipment, and may thus cause problems in tunnels and under bridges and be a hazard to maintenance personnel.

(2) Autotransformers are bulkier and more expensive than booster transformers.

(3) The autotransformer magnetizing current can cause protection problems.[6.5]

6.3 Track Sectioning Details

In ac electrified sections substations are usually located at intervals of 30 to 50 km, and a feeding sectioning post (gap breaker station) is installed midway between substations so as to enable the adjoining substation to extend the feeding range. Auxiliary sectioning posts also are installed in places where the division of feeding units is preferable, to obtain power interruption for maintenance work or for power failures.[6.6]

At the section posts, changeover circuits which eliminate the requirement for the trains to notch off were developed. The changeover circuit breakers installed at section posts must work at each passage of a train. Special circuit breakers for frequent switching were developed to insure correct performance. Furthermore, standby circuit breakers were installed to insure normal operation of trains.

Another notable feature found in the feeding system is the parallel feeding (double-end-feed) system used at the point of the section post where the phase difference between adjacent substations is very small - the first time such a system has ever been employed on the ac electrified sections in Japan - and successful results have been attained, such as the elimination of transient phenomena due to switching. A schematic diagram of the power feeding system is shown in Fig. 6.2.

6.4 Summary

In Japan power is supplied at two voltages and frequencies, 20 and 25 kV - 50 and 60 Hz, to 4200 route km of electrified track. Most power is supplied from the utility 220 kV and 270 kV network. Static frequency converter stations are used in some locations to change 50 Hz power to 60 Hz. The catenary is end-fed from Scott-connected and modified Woodbridge-connected transformers, with two transformers usually located at each substation. Substations are spaced 30 to 50 km apart. The catenary between substations can be double-end-fed where the phase difference is small. Special changeover circuits at sectioning posts prevent the train from becoming deenergized. Booster transformers have been used to reduce interference; however, on all new electrification, autotransformers will be used because they allow increased substation spacing, minimize interference, and are more economical.

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6.6 Railway Directory and Yearbook, 1977, Eighty-second year of publication, published by IPC Transport Press Limited, London, England, 1976.

7.0 FEDERAL REPUBLIC OF GERMANY (WEST GERMANY)

Several different electrification systems were in use in Germany prior to 1912, but at that time the railroads in the eastern regions decided to adopt the single-phase, 15 kV, 16 2/3 Hz electrification scheme already in use in Austria, Sweden, Norway and Switzerland. Today all of West Germany uses 15 kV, 16 2/3 Hz power for its standard ac railroad electrification system. The map of Fig. 7.1 and Table 7-1 show the extent of electrification for the 10,000 electrified route km of the Deutsche Bundesbahn (DB) of West Germany.

7.1 Source of Electric Power

Small-capacity generators were first used to supply the railroad with 16 2/3 Hz power along with synchronous converters. These converters were motor-generator sets which used the 3-phase, 50 Hz industrial power to obtain single-phase 16 2/3 Hz power. Today, larger generators and newer static frequency converter sets supply power to the catenary.

German railroads developed a high-voltage, 110 kV transmission system to efficiently deliver power to the catenary, while adding reliability to the supply by tying points together with two independent transmission lines (Fig. 7.2). Supply points in the system are generally spaced 60 to 80 km apart.[7.1]

7.2 Method of Supplying Catenary

The catenary power is supplied by railroad substations which are fed from the 110 kV transmission system, but may also be connected to the 3-phase, 50 Hz commercial system through portable converter

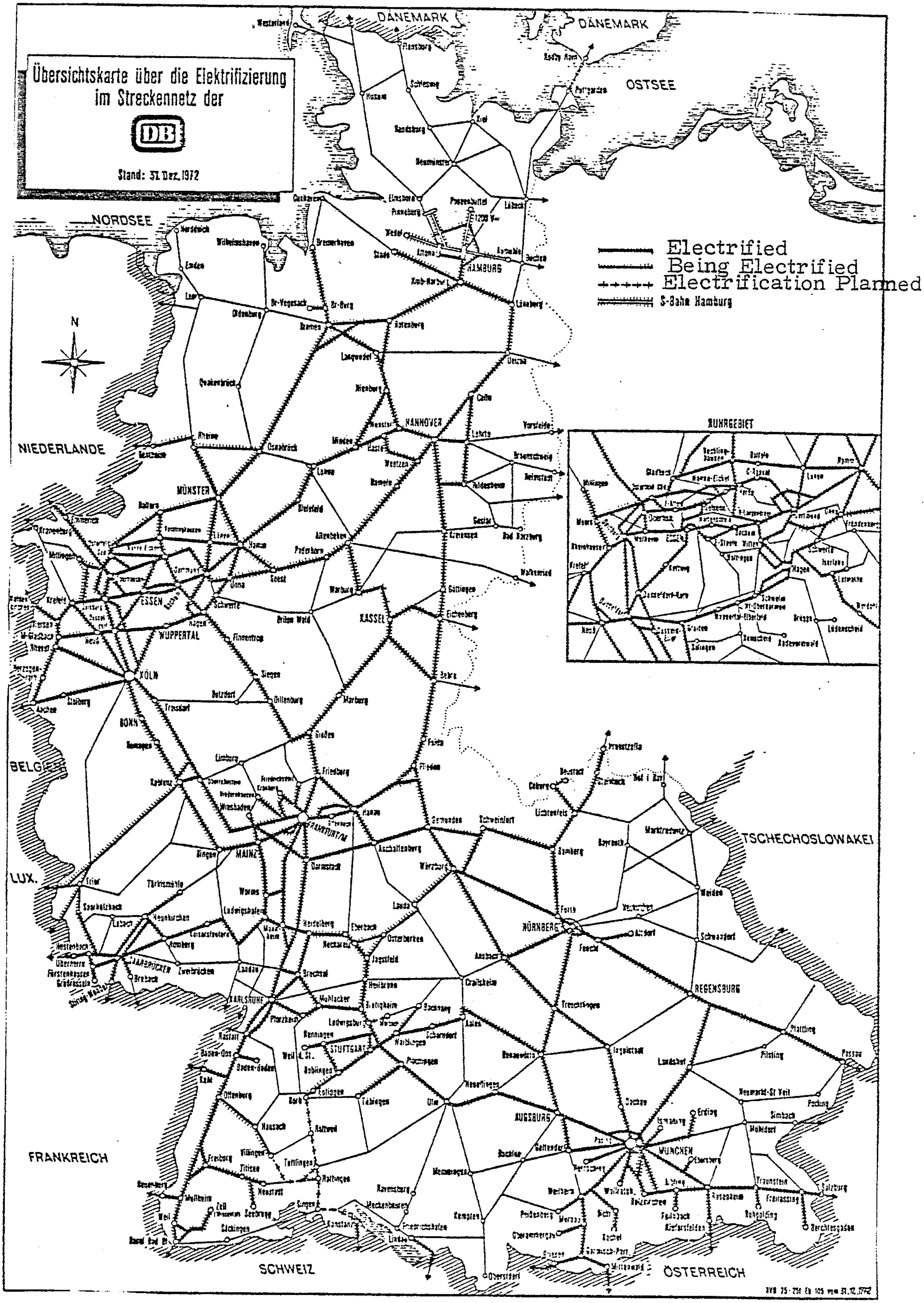

Fig. 7.1 Electrification System for West Germany (DB) in 1972.

(Ref. 7.4)

Table 7-1

Extent of Electrification in West Germany at End of 1977. (Ref. 7.5)

Country, Railway, and Lines Electrified	Length Electrified		Voltage	System of Electrification	Conductor	Year Electrified
	Route Km.	All Track Km.				
Germany—						
Deutsche Bundesbahn (Federal Republic)—		..	..	..	..	..
German Federal Railways	9,929	..	15,000	1/16⅔	O H	1904-75
Hamburg City Line . .	82	..	1,200	D.C.	3 R	1907-70
Total . . .	10,011	..	..	..	..	..

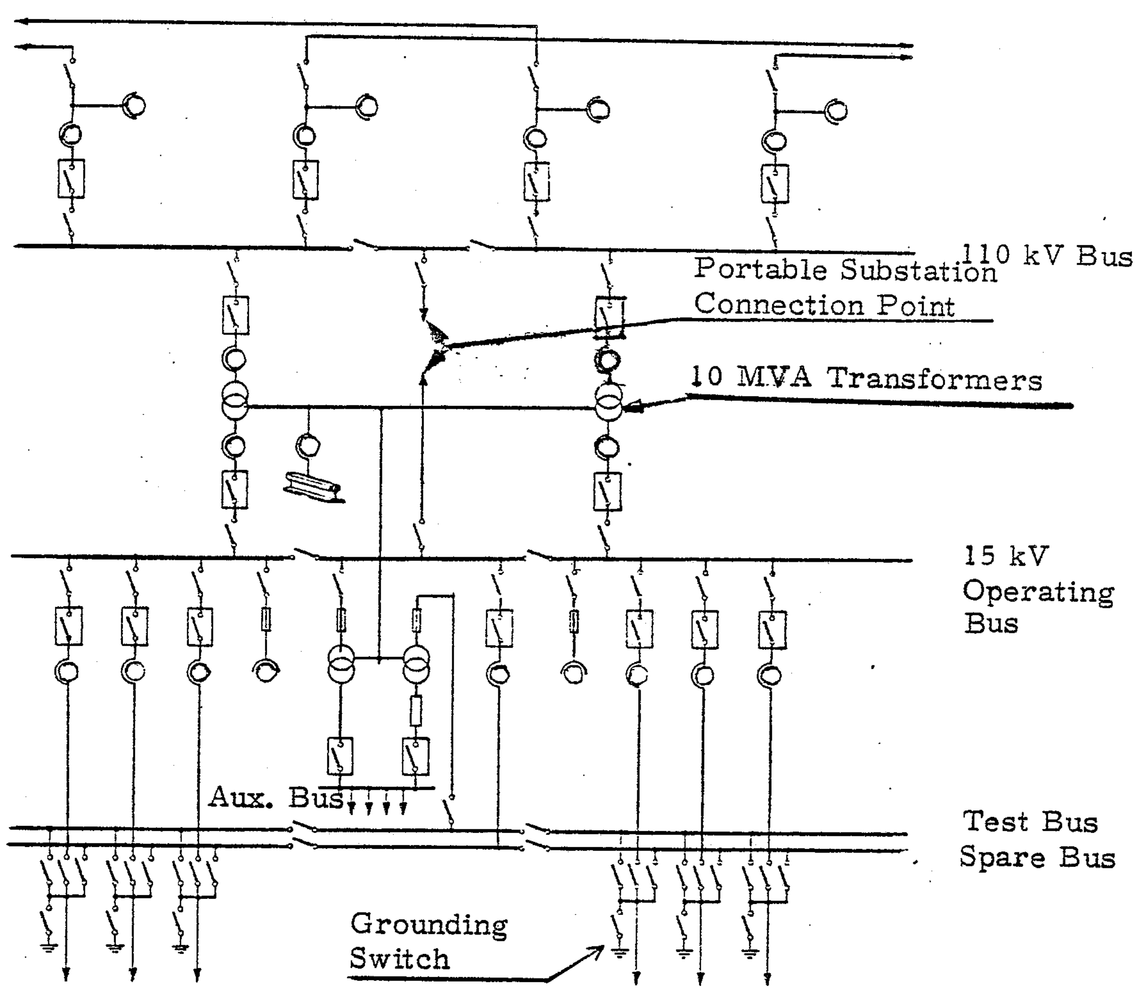

Fig. 7.2 Typical 15 kV-16 2/3 Hz Substation Supplying Three Tracks in Both Directions of Travel. (Ref. 7.1)

Legend:

Potential Transformer

Current Transformer

substations located nearby (see Fig. 7.2). At points where two separate 110 kV lines enter a substation, two 110 kV to 15 kV transformers are provided to feed the 15 kV operating bus. These transformers are typically rated at 10 MVA and only one is usually required to operate at a time.[7.1]

Power is supplied to a 30 to 40 km section of catenary in each direction through individual circuit breakers and isolating switches that are connected to the 15 kV operating bus as shown in Figs. 7.2 and 7.3.

7.3 Track Sectioning Details

A coupling (track sectioning) station is located between each railroad supply substation. These coupling stations allow the DB to feed power to a section of catenary from both adjoining supply points, thereby reinforcing the supply and also allowing any substation to go off-line for maintenance requirements (Fig. 7.3, 7.4). The coupling stations consist of mast switches located at the appropriate locations along the track. Fig. 7.4 shows the presently-used coupling circuit as well as future variations.[7.3] At present the catenaries of the two parallel tracks are only cross-connected at the substations and coupling stations. Future plans are to provide additional connections throughout its length to reduce the impedance at the vehicle.

7.4 Summary

In the Federal Republic of Germany a dedicated 15 kV- 16 2/3 Hz system supplies power to 9930 route-km (1977). Special generators, frequency converters and 110 kV transmission lines supply power to

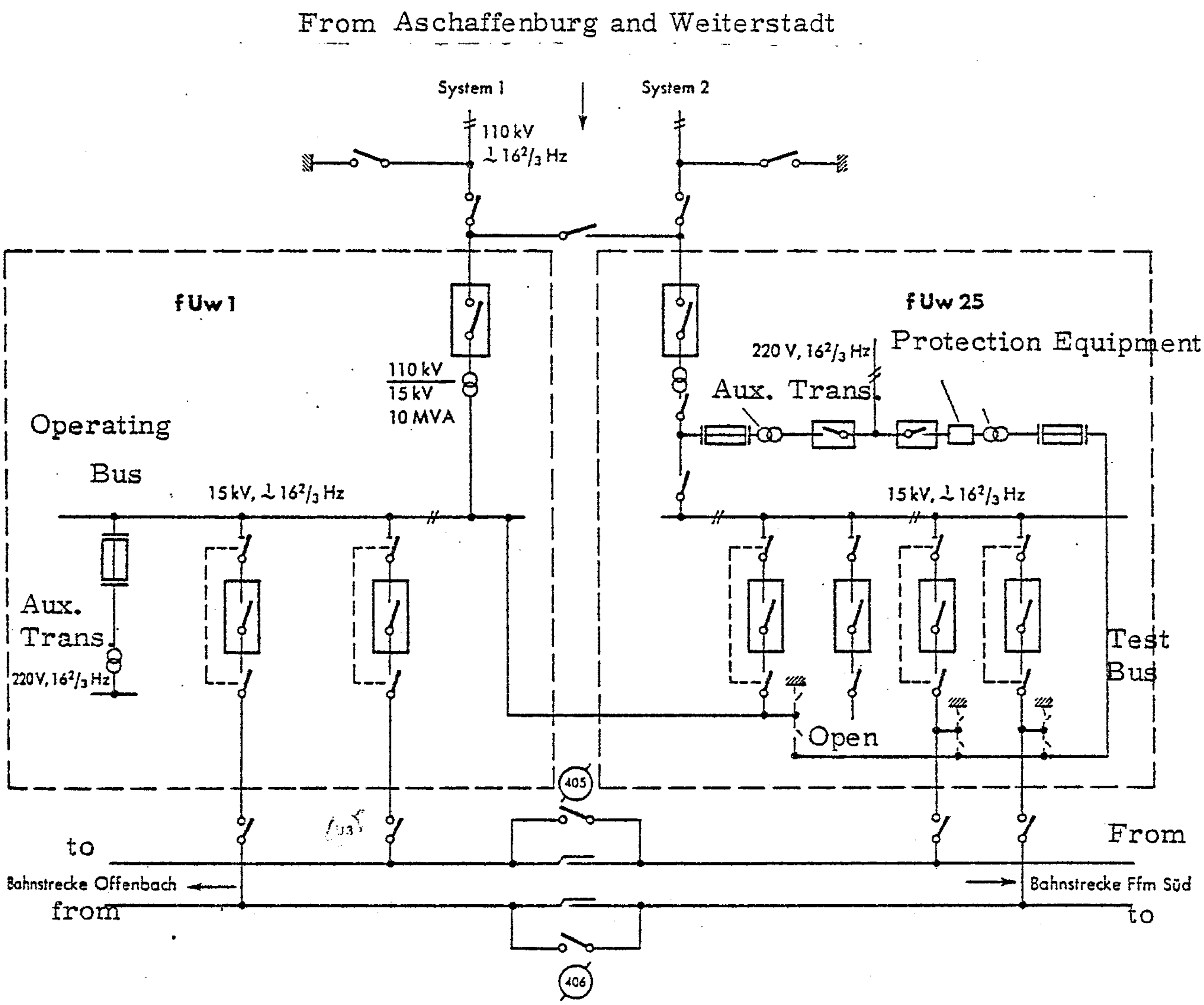

Fig. 7.3 Typical 15 kV-16 2/3 Hz Substation Supplying Two Tracks in Both Directions. (Ref. 7.4)

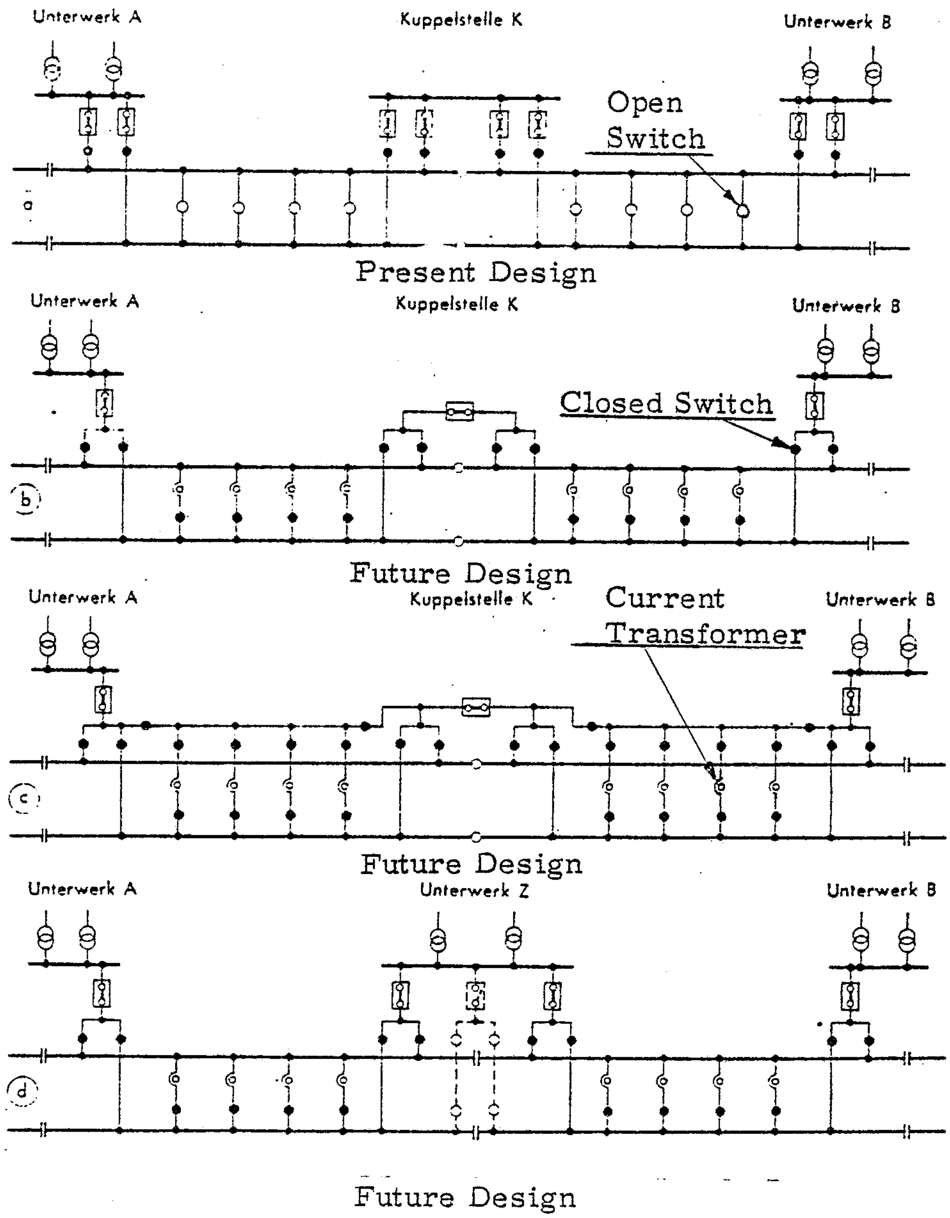

Fig. 7.4 Coupling Circuits (Present and Future) for DB. (Ref. 7.3).

the railroad substations. The substations contain two transformers, with one used as a spare. The substations are spaced 60 to 80 km apart and a section of catenary located between two substations can be double-end-fed.

7.5 References

7.1 Werner, M., "Die Stromversorgung Fur Die Elektrische Zugforderung Der Deutschen Bundesbahn"; (The Electricity Supply for the Electrical Train Traction of the German Federal Railway); Etz, 14. Jahrgang, 6 August 1962, Heft 16, PP 417-425.

7.2 Krienitz, G., "Entwicklung Und Stand Der Elektrifizierung Mit Einphasen-Wechselstrom"; (Development and Present Status of the Electrification with Single-Phase Alternating Current); Glasers Annalen, Eisenbahnwesen Und Verkehrstechnik, 91, Jahrgang/ Heft 5, Berlin, Mai 1967, PP 129-136.

7.3 Scheiber, E., "Aktuelle Fragen Der Stromversorgung Fur Die Elektrifizierten Strecken Der Deutschen Bundesbahn"; (Important Questions on the Power Supply for the Electrified Routes of the German Federal Railways); Elektrische Bahnen, Heft 5 (42. Jahrgang 1971), PP 98-104.

7.4 Bauermeister, K., "Der Elektrische Zugbetrieb Der Deutschen Bundesbahn Im Jahre 1972"; (The

Electric Railroad Operations of the German Federal Railways in the Year 1972)] Elektrische Bahnen, 44 (1973) H. 1, PP 2-21.

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Kunzel, H. "Stromversorgungsanlagen Der Munchner S-Bahn Anlablich Der XX Olympischen Sommerspiele"; (Power Supply Installations of the Munich S-Bahn Which Started for the 20th Summer Olympics); Elektrische Bahnen, 44 (1973) H. 3, PP 62-65.

8.0 SWEDEN

Electrification made its debut on Swedish railways (SJ) in 1915, when the single track Kiruna-Riksgränsen route (140 km), which carries heavy ore traffic in an Arctic climate, was electrified at 15 kV 15 Hz. This single-phase system was supplied from SJ's own generators located in the Porjus power plant via an 80 kV single-phase transmission line running to 80/15 kV transformer stations. Further electrification on routes adjoining the Kiruna-Riksgränsen route incorporated the same principles. As electrification continued in other parts of the railway network, it was decided to use substations with synchronous converters supplied from the public 50 Hz 3-phase grid. This system, which operates on 15 kV 16 2/3 Hz, is now used throughout the entire SJ electrified network. During recent years, synchronous converters have been replaced by static converters in some substations.[8.1] There are no railroad sections in Sweden that operate with directly supplied 50 Hz power from the public grid.

A map of Sweden showing the extent of the SJ Railway network is shown in Fig. 8.1. As of 1977, about 7500 route-km of railroad has been electrified as shown in Table 8-1.

8.1 Source of Electric Power

In addition to the converter units, each converter station also contains switchgear equipment that receives the incoming 3-phase 50 Hz 6 kV transmission line power and sends out single-phase 16 2/3 Hz 15 kV power to the overhead contact line network. Space is also provided for control and auxiliary equipment in the station, and there are accommodations for operating personnel.

Interconnection of the converter stations to a common contact line helps to:

- Reduce voltage drop in the overhead contact line
- Smooth out peak loads on the converter stations

Three sizes of synchronous converters are used: 3.1 MVA, 5.8 MVA and 10 MVA. Each converter, consisting of a 3-phase motor, single-phase generator and exciters, is mounted on a 5-to-6 axle railway wagon. An equipment wagon containing high-voltage breakers, a single-phase transformer, control equipment, etc., is coupled directly to each converter wagon. Together, they form a mobile converter unit. The converter units are installed in a converter station hall, 2-to-5 units per station.

Toward the end of the 1960's, it became technically possible and economically feasible to design static frequency converters for railway use. After extensive testing, SJ decided to install static converters to replace synchronous converters, as the latter wear out. The first generation of static frequency converters were built with capacities of 15 MVA. As shown in the diagram of Fig. 8.2, the static converters are basically thyristor-type cycloconverters. These converters are stationary and offer the following advantages compared with synchronous converters they replace:

- Higher efficiency
- Quicker starting (standby units can be tied-in faster if power requirements should rise rapidly)
- Less preventive maintenance
- Less expensive per MVA[8.1]

SJ RAILWAY NETWORK
1975-06-30

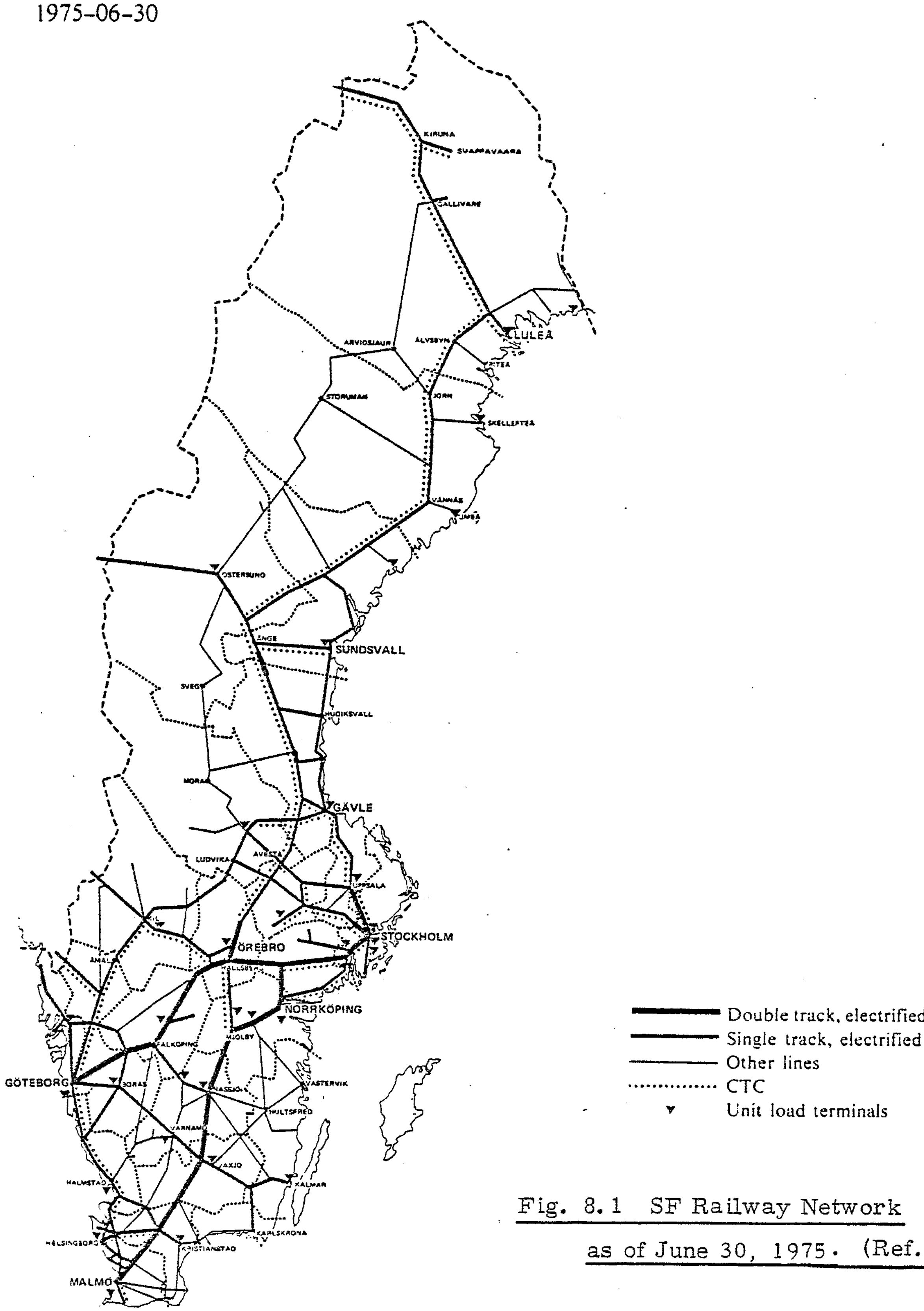

Fig. 8.1 SF Railway Network as of June 30, 1975. (Ref. 8.1)

Table 8-1

Extent of Electrification in Sweden as of 1977. Ref. 8.2)

Country, Railway, and Lines Electrified	Length Electrified		Voltage	System of Electrification	Conductor	Year Electrified
	Route Km.	All Track Km.				
Sweden—						
State Railways—						
Lulea - Riksgränsen - Norwegian Border branch lines to Svappavaara,	485	..	15,000	1/16⅔	O H	1915-22
Koskullskulle	...	..	...	..	..	1923-64
Boden C - Bräcke - Avesta Stockholm C	1,147	..	15,000	1/16⅔	O H	1926-42
Långsele - Härnösand - Gävle C-Uppsala C	531	..	15,000	1/16⅔	O H	1937-58
Ånge-Sundsvall C	95	..	15,000	1/16⅔	O H	1942
Ljusdal-Hudiksvall	61	..	15,000	1/16⅔	O H	1959
Kilafors-Söderhamn	33	..	15,000	1/16⅔	O H	1953
Gävle-Ockelbo	38	..	15,000	1/16⅔	O H	1942
Bräcke - Östersund C. - Storlien-Norwegian Border	237	..	15,000	1/16⅔	O H	1939-45
Avesta-Mjölby	253	..	15,000	1/16⅔	O H	1932-34
Avesta-Borlänge	64	..	15,000	1/16⅔	O H	1948
Örebro S.-Svartå	50	..	15,000	1/16⅔	O H	1937
Gävle C-Falun C-Kil-Göteborg-C.	570	..	15,000	1/16⅔	O H	1939-46
Ludvika - Tillberga - Tomteboda with branch line to Snyten	210	..	15,000	1/16⅔	O H	1946-56
Sala - Tillberga - Västerås - Köping	73	..	15,000	1/16⅔	O H	1947-56
Laxå - Kil - Charlottenberg - Norwegian Border	209	..	15,000	1/16⅔	O H	1937-51
Mellerud - Mon - Norwegian Border	64	..	15,000	1/16⅔	O H	1939
Stockholm C - Järna - Hallsberg-Göteborg C.	459	..	15,000	1/16⅔	O H	1926
Älvsjö-Nynäshamn	55	..	15,000	1/16⅔	O H	1962
Järna - Mjölby - Malmö C. - Trelleborg F.	584	..	15,000	1/16⅔	O H	1932-33
Södertälje S - Eskilstuna with branch lines to Strängnäs	97	..	15,000	1/16⅔	O H	1936
Katrineholm-Åby	41	..	15,000	1/16⅔	O H	1932
Skövde-Karlsborg	44	..	15,000	1/16⅔	O H	1937
Falköping C-Nässjö	113	..	15,000	1/16⅔	O H	1932
Strömstad - Uddevalla C - Göteborg Olskroken and Lysekil branch	213	..	15,000	1/16⅔	O H	1939-50
Göteborg C - Ängelholm-Arlöv	294	..	15,000	1/16⅔	O H	1933-36
Uddevalla C - Borås C - Varberg	217	..	15,000	1/16⅔	O H	1949
		..	15,000	1/16⅔	O H	1949
Almedal-Borås C-Alvesta	216	..	15,000	1/16⅔	O H	1936-62
Alvesta - Karlskrona - Kalmar	188	..	15,000	1/16⅔	O H	1954-55
Veinge-Hässleholm	72	..	15,000	1/16⅔	O H	1935
Ängelholm-Helsingborg F	26	..	15,000	1/16⅔	O H	1937
Helsingborg-Kristianstad C.	107	..	15,000	1/16⅔	O H	1943-55
Helsingborg-Eslöv	45	..	15,000	1/16⅔	O H	1944
Åstorp-Höganäs	27	..	15,000	1/16⅔	O H	1937
Lund C - Landskrona-Billeberga	42	..	15,000	1/16⅔	O H	1948-49
Total, Standard Gauge.	6,930	10,992	..	..	..	..
Narrow gauge (private):						
Rimbo-Stockholm Ö	55	..	1,500	D.C.	O H	1895-49
Roslags Näsby-Österskär	18	..	1,500	D.C.	O H	1939
Djursholms Ösby-Eddavägen	5	..	1,500	D.C.	O H	1895-01
Djursholms Ösby-Näsbypark	5	..	1,500	D.C.	O H	1910-37
Private Railways—						
Trafik AB Saltsjöfart, Saltsjöbanan and Igelboda-Solsidan	18	27	1,350	D.C.	O H	1913
Grängesberg-Oxelösund Rly.	300	446	15,000	1/16⅔	O H	1947-56
Nordmark-Klarälven Railway (narrow gauge)—						
Karlstad Ö-Finnshyttan	150	} 200 {	15,000	1/16⅔	O H	1920
Karlstad Ö-Skoghall	10		15,000	1/16⅔	O H	1941
Total privately owned railways	561	779	..	..	..	..
Total electrified lines in Sweden	7,491	11,771	..	..	..	..

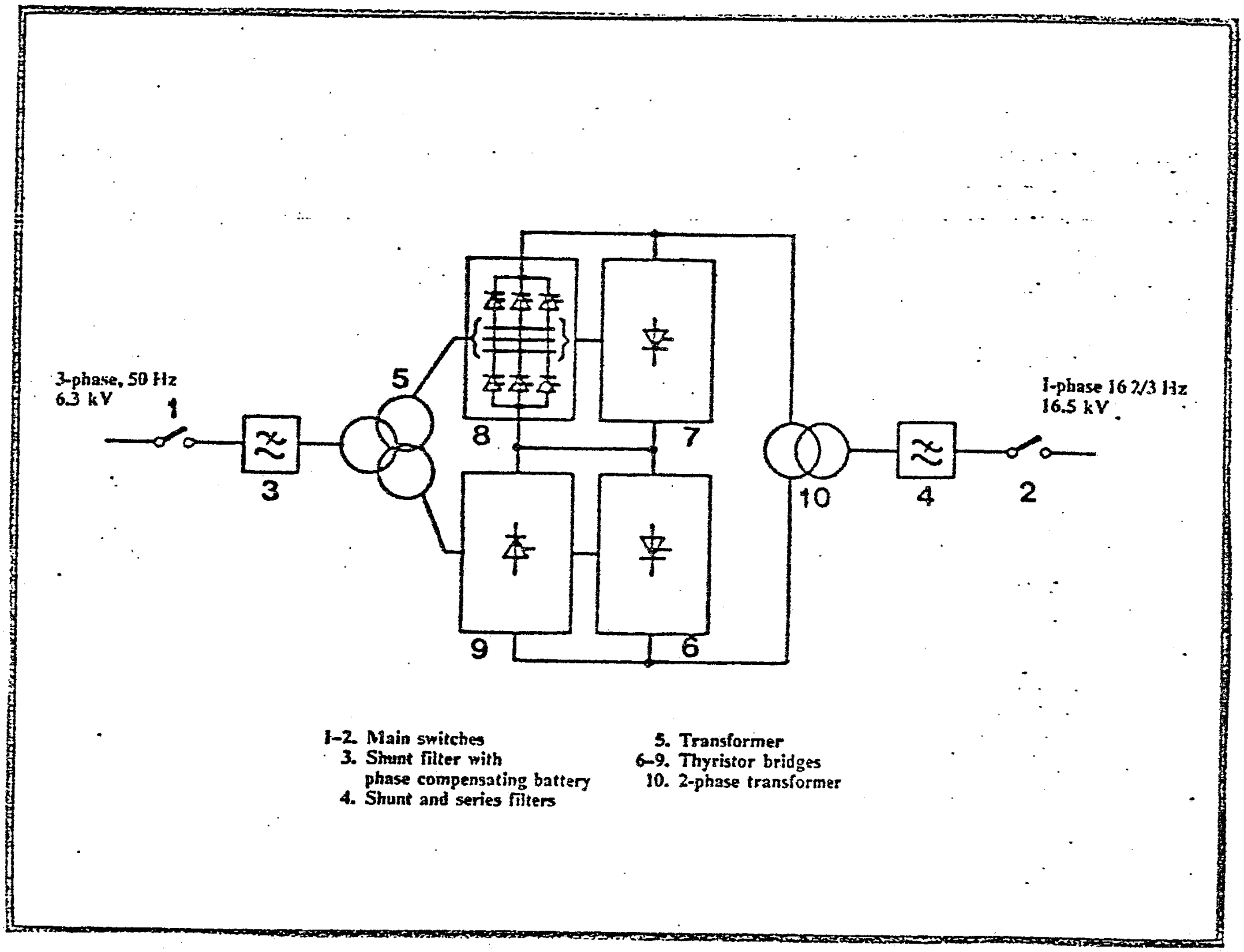

Fig. 8.2 Block Diagram of Static Frequency Converter Used in Sweden. (Ref. 8.1)

8.2 Method of Supplying Catenary

Under normal operation single-phase power is fed to each section of catenary through circuit breakers. The overhead contact line circuit breakers enable normal loads to be connected and disconnected. Moreover, they quickly break the circuit if a fault current (short-circuit current) occurs, thus minimizing damage at the point where the fault occurred.[8.1]

8.3 Track Sectioning Details

Each section of catenary is separated from the adjacent sections by insulated overlaps. Remotely controlled switching stations located between the converter stations are provided with breakers that cut out the appropriate circuits in the event of a fault.[8.1]

8.4 Summary

In Sweden a dedicated 15 kV 16 2/3 Hz electrification system supplies power to 7500 route km (1977) of track. Special generators, frequency converters and 6 kV, 3-phase, 50 Hz transmission lines which interconnect all converter supply points provide power to the substations. Each section of catenary is separated from the adjacent sections by insulated overlaps. Booster transformers and return conductors are used where ground resistance is high.

8.5 References

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8.2 Railway Directory and Yearbook, 1977, Eighty-second year of publication, published by IPC Transport Press Limited, London, England, 1976.

9.0 SWITZERLAND

Switzerland's railways are the most highly electrified by **far**, since 99.5 percent of the government-operated Swiss Federal Railway's (SFR's) and 99.3 percent of all private railways are now electrified. A map of the SFR is provided in Figs. 9.1 and 9.2. Table 9-1 shows details of the extent of electrification in all Swiss railroads - privately-operated and government-operated. The SFR operates 2911 route km, which is over half the 5062 route km in current use in Switzerland; the balance is privately operated.

Switzerland's undulating topography, which results in ruling grades of 1 in 80 in the 'flat' country and of 1 in 38 in the mountainous areas, the absence of coal and oil resources and an abundance of hydro-electric power, coupled with the presence of innovative manufacturers of electrical machinery led to the early implementation of electric traction.

In view of the obvious operational and economical advantages of electric traction compared to steam, a decision of principle was taken for full electrification of the SFR using 15 kV 16 2/3 Hz power, as early as 1914. The acute coal shortage that immediately followed during World War I gave this decision strong support.[9.1]

The privately-owned railways were responsible for the layout of the various mountain railways and funiculars. One of the best known of these is the Gornergrat Railway from Zermatt to the Gornergrat, from which the traveller can enjoy a magnificant view of a continuous line of huge snow and glacier-covered mountains. The Gornergrat Railway uses three-phase ac power at 50 Hz and 725 volts.[9.2]

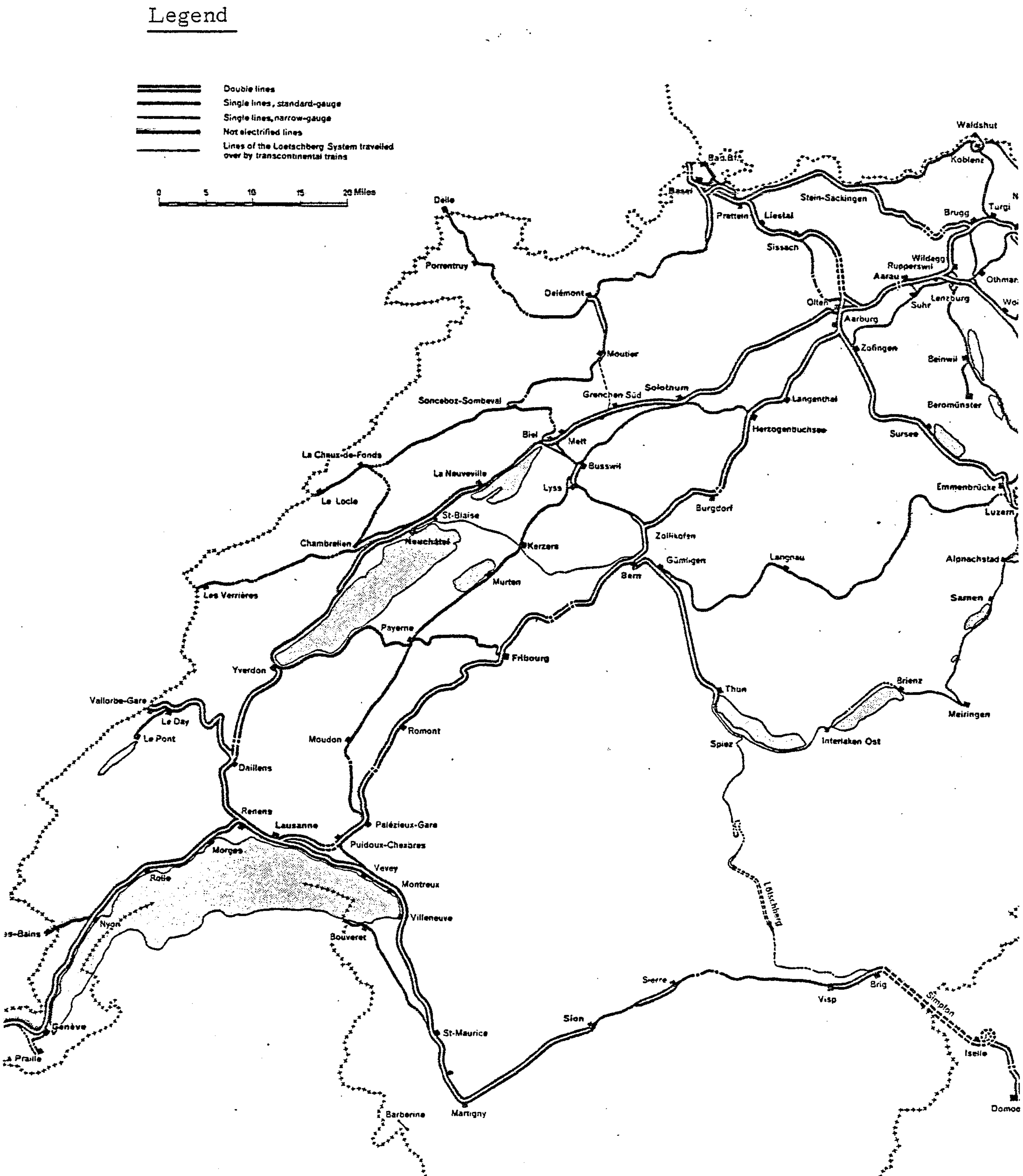


Fig. 9.1 Network of the Swiss Federal Railways in 1955 (Western Portion). (Ref. 9.2)

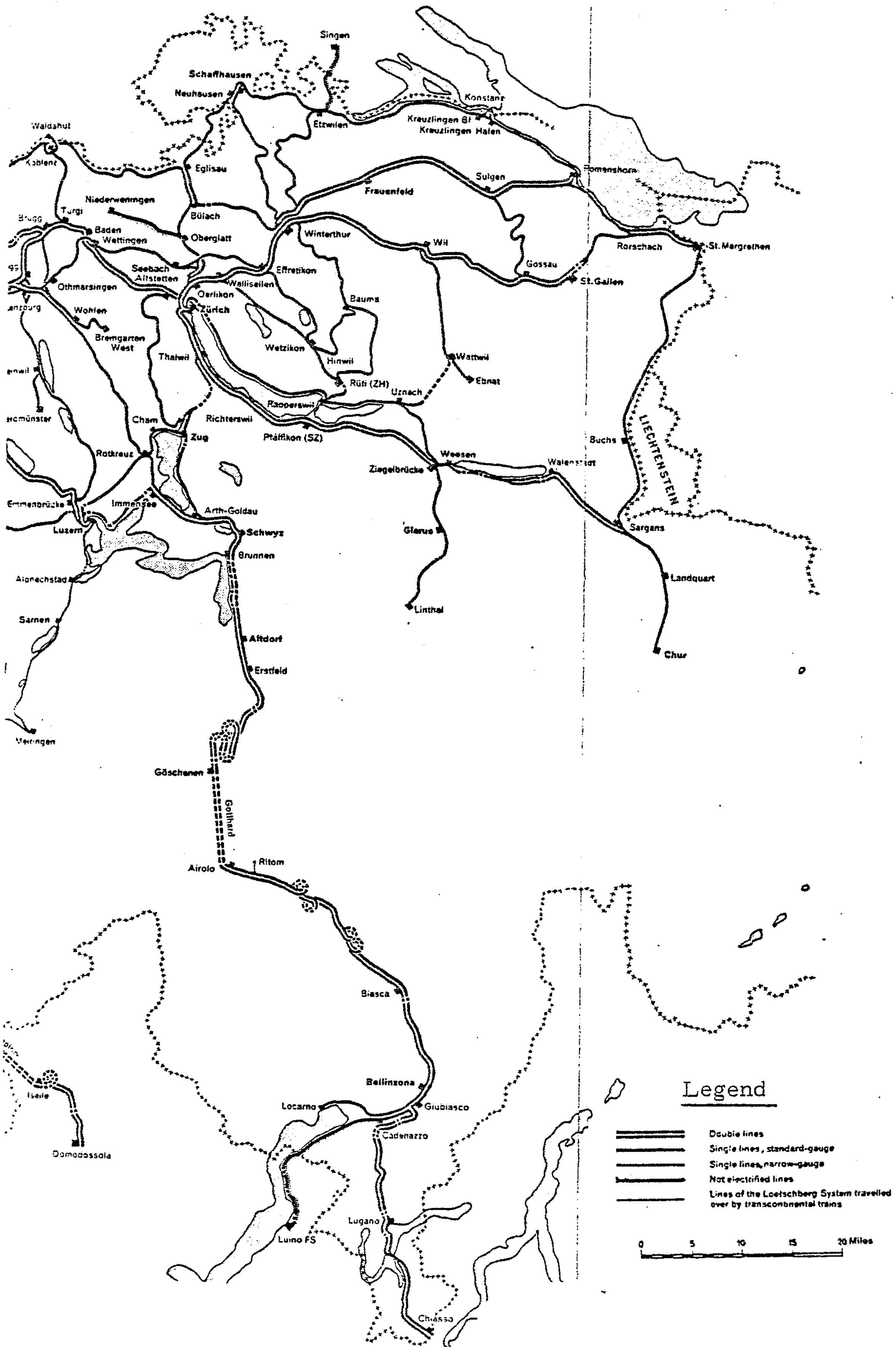


Fig. 9. 2 Network of the Swiss Federal Railways in 1955 (Eastern Portion). (Ref. 9.2)

Table 9-1

Extent of Electrification in Switzerland in 1977. (Ref. 9.4)

Country, Railway, and Lines Electrified		Length Electrified Route K.m.	Length Electrified All Track K.m.	Voltage	System of Electrification	Conductor	Year Electrified
Switzerland—							
Swiss Federal Railways—							
General System (standard gauge)	A	2,818	6,301	15,000	1/16⅔	O H	1906-60
	A	19	39	1,500	D.C.	O H	1956
Brünig Line (metre gauge)	A+R	74	93	15,000	1/16⅔	O H	1941-42
Private Railways (standard gauge)—							
Berne-Lötschberg-Simplon Railway and other lines	A	235	382	15,000	1/16⅔	O H	1910-28
Bodensee-Toggenburg Rly.	A	56	73	15,000	1/16⅔	O H	1931-32
Emmental-Burgdorf-Thun Railway and other lines	A	100	218	15,000	1/16⅔	O H	1899, 1919 1932-33
Gruyère-Fribourg-Morat Railway (standard gauge system only)	A	43	53	15,000	1/16⅔	O H	1903, 1946 1947
Martigny-Orsières Rly.	A	25	30	15,000	1/16⅔	O H	1910
South-Eastern Railway (Wädenswil-Einsiedeln; Rapperswil-Arth-Goldau)	A	47	58	15,000	1/16⅔	O H	1939
Rorschach-Heiden Rly.	A+R	6	8	15,000	1/16⅔	O H	1930
Other lines	A	137	181	various	various	O H	over many years
Private Railways (narrow gauge)—							
Appenzell Railway	A	32	43	1,600	D.C.	O H	1912, 33
Bière-Apples-Morges Rly.	A	30	33	15,000	1/16⅔	O H	1943
Jura Railways (meter gauge system only)	A	74	80	1,500	D.C.	O H	1913
Furka-Oberalp Rly.	A+R	100	115	11,500	1/16⅔	O H	1940, 42
Locarno-Camedo	A	20	23	1,200	D.C.	O H	1923
Gruyère-Fribourg-Morat Railway (meter gauge system only)	A	50	58	900	D.C.	O H	1901-12
Martigny-Châtelard	A+R	18	23	830	D.C.	3 R/O H	1906
Montreux-Bernese Oberland Railway	A	75	89	900	D.C.	O H	1901, 12
Nyon-St-Cergue-Morez Railway	A	27	31	2,200	D.C.	O H	1916, 21
Rhaetian Railways		390	404				
Main Routes	A	(275)		11,000	1/16⅔	O H	1913-22
Chur-Arosa	A	(26)		2,000	D.C.	O H	1914
Bernina Railway	A	(61)		1,000	D.C.	O H	1908-10
Castione-Mesocco	A	(28)		1,500	D.C.	O H	1907
St. Gallen-Gais-Appenzell Railway	A+R	28	35	1,700	D.C.	O H	1931
Solothurn-Zollikofen-Berne Railway	A	37	55	1,200	D.C.	O H	1912-16 1923-24
Berre-Worb		25	29	800/1,200	D.C.	O H	1910-13
Brig-Visp (Viège)-Zermatt Railway	A+R	43	53	11,500	1/16⅔	O H	1929-30
Waldenburg Railway (750 mm. gauge)	A	13	16	1,500	D.C.	O H	1953
Other lines	A	300	364	various	various	O H	over many years
Other lines	A+R	105	132	various	various	O H	
Other lines (also standard metre and 800 mm. gauge)	R	47	101	various	various	O H	
Total		5,062	9,117	..	..	..	..

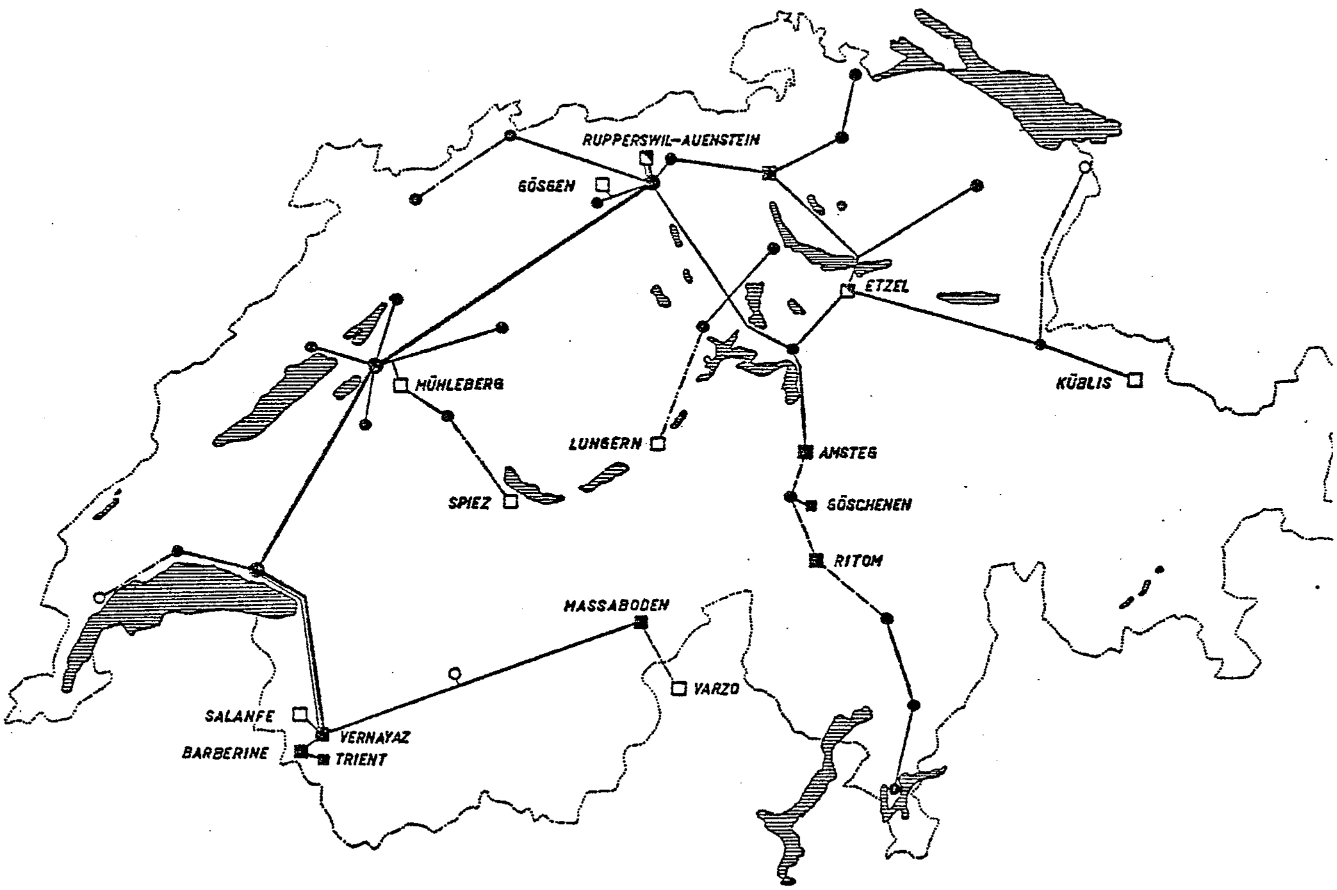
Switzerland: The Simplon Tunnel section, opened as a three-phase line in 1906 and later extended on this system to Sion (Sitten), and the Seethal Railway, electrified on the single-phase, 25 cycles system in 1910, were changed to the standard single-phase, 16⅔ cycles system in 1930. The Burgdorf-Thun and Hasle-Rüegsau-Langnau lines were originally three-phase, 750 volts, 40 cycles, but were converted to single phase in 1932-33, when the Solothurn-Münster (Moutier) and Solothurn-Burgdorf lines were electrified. The Fribourg-Morat line, electrified at 850V d.c. 3rd rail in 1903, was converted to the standard single-phase A.C. system in 1947. A=adhesion lines. A+R=adhesion and rack working. R=plain rack working.

9.1 Source of Electric Power

The decision to use single-phase ac power at a frequency of 16 2/3 Hz necessitated the building of railway-owned power stations, because it was impossible to supply the railways directly with this kind of current from existing hydro-electric power plants, which usually generated three-phase ac power at 50 Hz. The construction of exclusive converter stations, which would have been very costly, was out of the question. Nevertheless, the frequency of 16 2/3 Hz, exactly one-third the frequency of the available 50 Hz three-phase power, was chosen to facilitate the conversion in special cases.

Fig. 9.3 shows a sketch map of the high-tension part of the energy supply system of the Swiss Federal Railways. The plotted system consists of the hydro-electric power stations, marked with squares, the network of the overhead and cabled supply lines, and the substations and transformer stations, marked with black and white circles. From the last-mentioned, the energy is directly transmitted to the overhead conductors of the railway lines.

The whole system can be divided into two large groups; one situated in the eastern and southern part of the country, and the other in the western part. As the eastern and southern group is unable to supply adequately the whole network in its corresponding area, so additional energy is required from the western power stations. The power is supplied from the very efficient plants at Barberine and Vernayaz at 132 kV to the main substations at Puidous, Kerzers and Rupperswil, where this voltage is stepped down to 66 kV - the voltage at which nearly all substations of the whole system are fed.



Power station (SFR-owned)	Overhead supply line	132 kW
Power station (joint-SFR and privately owned)	Overhead supply line	66 kW
Power station (privately owned)	Overhead supply line	33 kW
Main sub-station	Overhead supply line	15 kW
Sub-station	Cable supply line	66 kW
Converter sub-station		
Transformer station		

Fig. 9.3 Energy Supply System of the Swiss Federal Railways. (Ref. 9.2).

A great advantage of a high voltage supply system is the small voltage drop in the supply conductors, in comparison with the catenary voltage drops. Moreover, the copper losses of the supply conductors are considerably smaller than would be the case if a lower supply voltage were used, for instance, for dc traction power. It is, therefore, a characteristic feature of the energy supply system of the Swiss Federal Railways that only a small number of substations are required. Altogether there are three main power stations, 22 substations and three transformer stations. In addition, 7 power stations transmit current directly into the overhead conductors of the track so that the whole network is fed from only 35 points.

Approximately 64% of the required energy is generated by the exclusively railway-owned power stations and some 22% is supplied by the two so-called "combined" plants jointly owned and supervised by the Swiss Federal Railways and a privately-owned concern. In addition, a small number of private converter stations generate the remaining 14% of the total power required by the Swiss Federal Railways.[9.2]

The transformers at the substations range in size from 3 MVA to 27 MVA. Since all substations are tied together through the catenary, transformers with regulating devices are required at many locations to minimize unnecessary through currents.

9.2 Method of Supplying Catenary

From the electrical system diagram of Fig. 9.4 it is seen that each substation supplies power by separate feeders to the catenaries in each direction, as well as to the isolating section at each

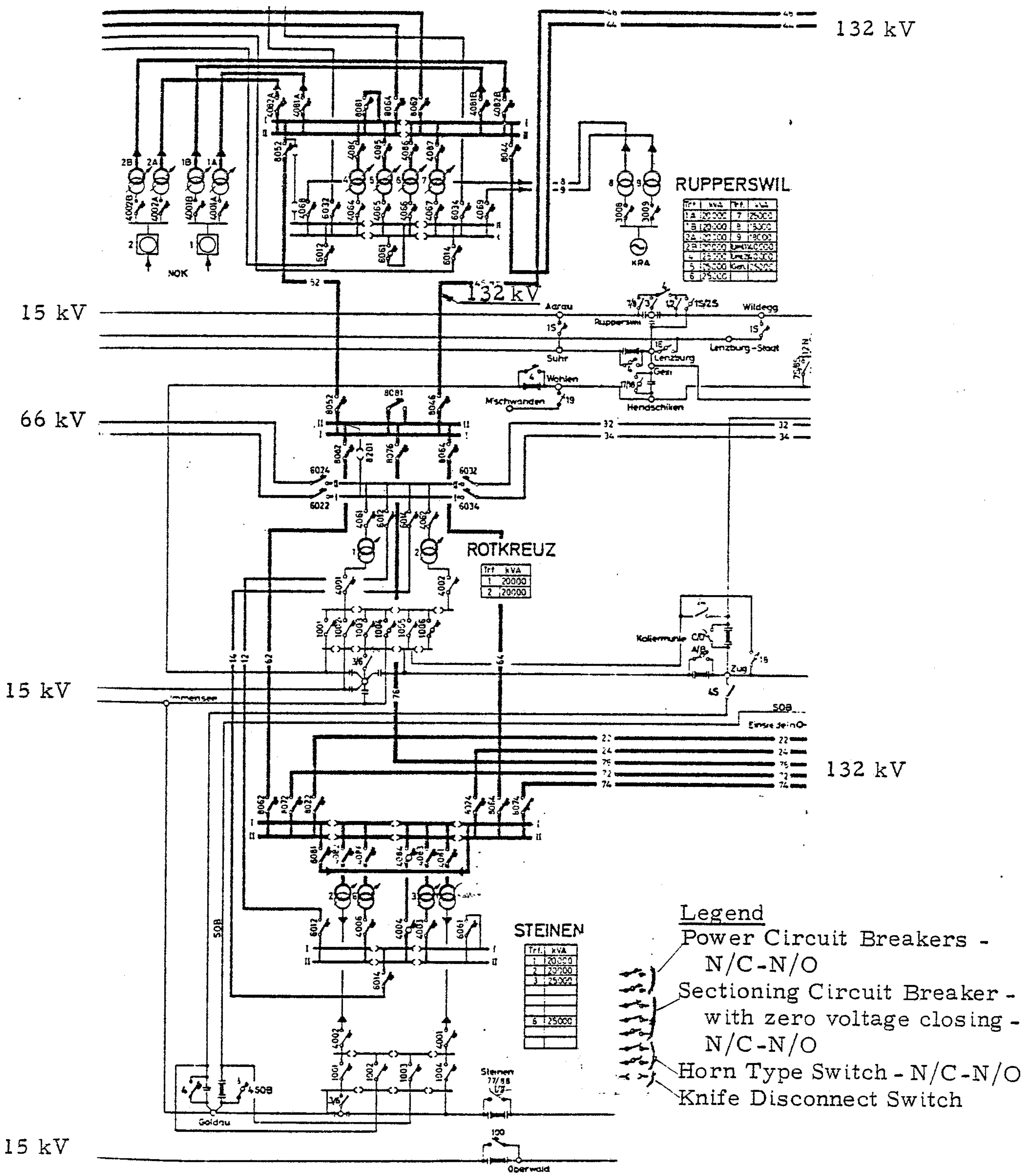


Fig. 9.4 Typical Electrical System Diagram for SFR Showing Supply Details. (Ref. 9.3)

substation. Circuit breakers protect the catenary by disconnecting it in the event of a fault.

9.3 Track Sectioning Details

As seen in Fig. 9.4 isolating sections are placed in the catenary between substations so that power can be removed from portions of the catenary for maintenance work. Most switches across these isolating sections are normally closed to reduce the voltage drop in the catenary.

9.4 Summary

In Switzerland a dedicated 15 kV 16 2/3 Hz system supplies 3500 route km (1977) of electrified railroad with power. Special generators, frequency converters and 132 kV and 66 kV transmission lines provide power to the substations. Substations contain more than one transformer and many of these transformers have voltage regulating capabilities to limit unnecessary circulating currents, since all substations are interconnected through the catenary.

9.5 References

9.1 Danuser, R., "The Case for Total Electrification"; Institution of Locomotive Engineers, Swiss Federal Railways, 10 March 1975.

9.2 Loosli, H., "Railway Electrification in Switzerland," Swiss Federal Railways, Berne, 1954 (book).

9.3 Drawing entitled "Einpoliges Schema. Ganzes Netz" (Single-phase Diagram - Entire Power Supply Network); Schweizerische Bundesbahnen. Abteilung Kraftwerke (Swiss Federal Railways, Electrical Division) Bern, April 1978.

9.4 Railway Directory and Yearbook, 1977, Eighty-second year of publication, published by IPC Transport Press Limited, London, England, 1976.

10.0 TAIWAN

The first section of the Taiwan Railroad between Taipei and Keelung was begun in 1887 and put into use in 1891. However, electrification did not begin until 1973. The Taiwan Railway Administration decided upon a 25 kV 60 Hz system, which would be fed from the local electric utility. The average distance between substations is 43 km for the three stages of the electrification. A map of Taiwan illustrating the layout of the railroads and the three stages of electrification is provided in Fig. 10.1. After all three stages are completed (1979) the railroad will have approximately 540 route km in electrified service.[10.1]

10.1 Source of Electric Power

As seen in Fig. 10.2, the electrical diagram for the first stage of Taiwan's electrification, three railroad substations are connected to the 69 kV, 3-phase industrial power system. In each of these substations two-10 MVA Scott-connected transformers are used to change the 3-phase industrial power to a 2-phase system for railroad use.

10.2 Method of Supplying Catenary

The catenary is fed by the same phase from both adjoining substations. Phase breaks are located at the supply points to separate the two different phases that are supplied from each substation.

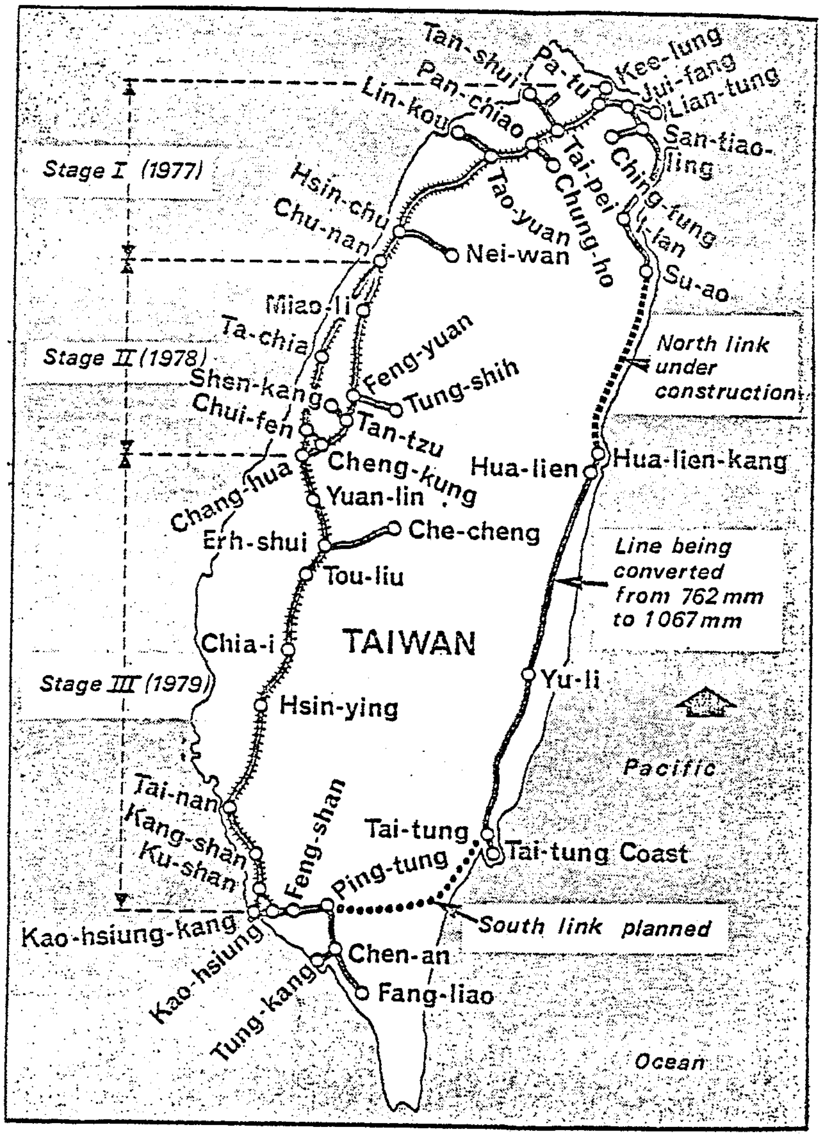


Fig. 10.1 Electrification System in Taiwan (3-Stage Plan). (Ref. 10.1)

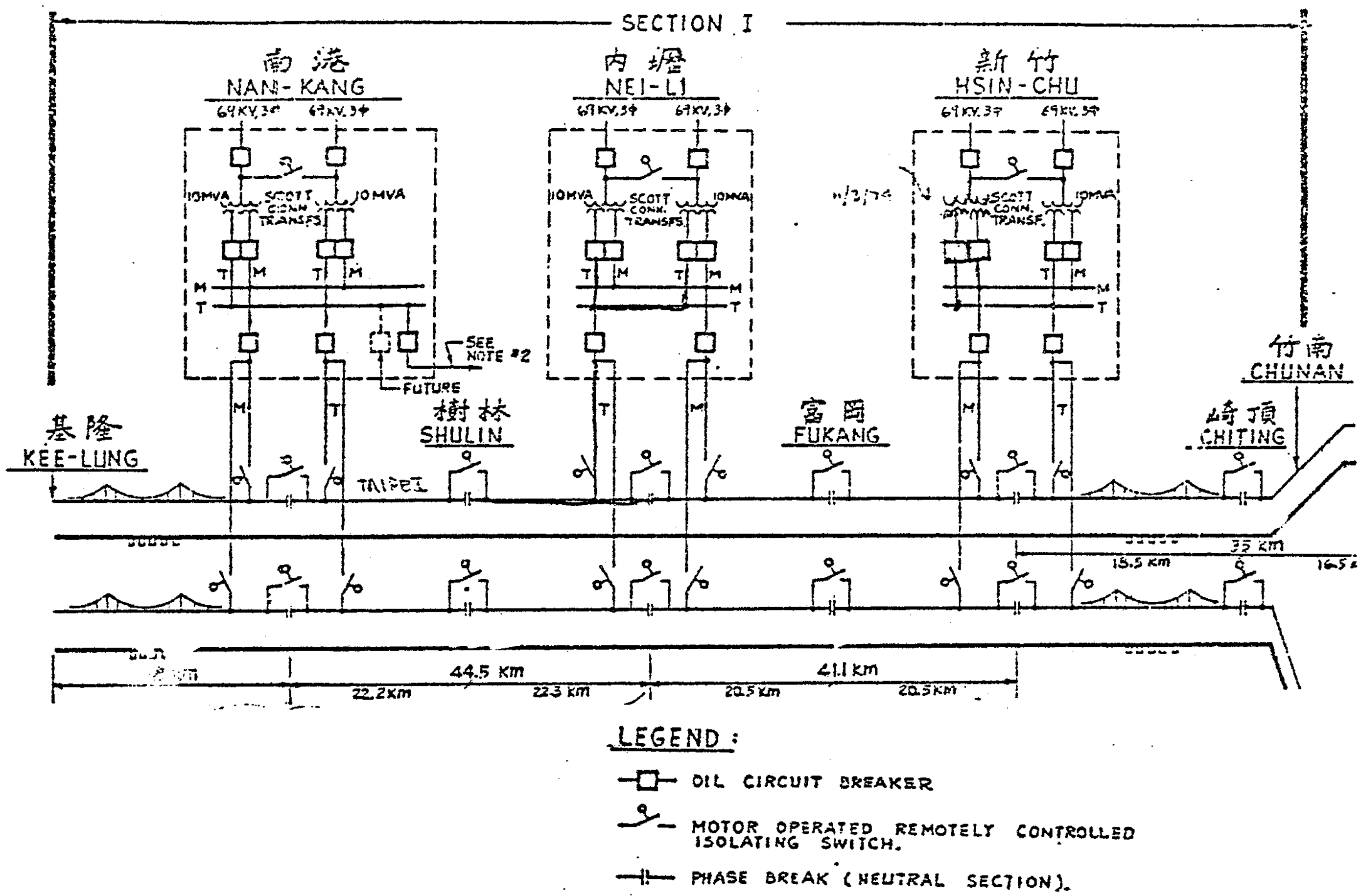


Fig. 10.2 Electrical Schematic Design for Stage 1 of Taiwan System. (Ref. 10.2)

10.3 Track Sectioning Details

At a point near the middle of each section of catenary a motor-operated remotely-controlled, isolating switch is installed across a phase break. In service this switch can be closed to provide power from both ends (double-end-feed) to a locomotive located between the supply points, if needed. The switch, in conjunction with the switches at the supply point phase break, is also used to isolate certain sections of catenary as required for maintenance purposes.

10.4 Summary

In Taiwan a new 25 kV 60 Hz electrification system is being built to supply 540 route km (1977) from the utility's 69 kV network. Most substations have two transformers and all transformers are Scott-connected. The distance between substations is 40 to 50 km. Neutral sections are located at the substations and midway between the substations, allowing the catenary to be double-end-fed.

10.5 References

10.1 Railway Directory and Yearbook, 1977, Eighty-second year of publication, published by IPC Transport Press Limited, London, England, 1976.

10.2 Drawing No. TRA-S7-301, "Electrical Trunk Line System," dated Aug. 1973, for the Taiwanian Railway Administration Electrification Project, drawn by the International Engineering Co., Inc., San Francisco.

11.0 SOUTH AFRICA

At the end of 1975 a total of 4,800 route km, consisting of 10,558 single-track km, was electrified on the South African Railways (SAR) (Table 11-1). All of this electrification was installed with a 3,000 Vdc system.[11.1] However, recently two new lines have been built; one by South African Iron and Steel Industrial Corporation Ltd. (Iscor). This line links iron ore mines at Sishen with the deep-water port at Saldanha Bay, as shown in Fig. 11.1. It was transferred from Iscor ownership to SAR on April 1, 1978. This new 845 km line uses 50 kV ac power on the catenary. This voltage has only been used on one other railroad so far: the Black Mesa and Lake Powell line in the United States.[11.2] The other line built by SAR extends from Ermelo to Richards Bay for the principle purpose of hauling coal. This 410 km line uses 25 kV 50 Hz power.

11.1 Source of Electric Power

The power is supplied to the 25 kV substations from the industrial 88 kV and 132 kV 50 Hz transmission system located nearby. A portion of each substation is owned by the SAR, the balance of each substation is owned by the national utility, the Electric Supply Company (ESC). ESC owns the equipment on the high-voltage circuit and the step-down transformer, while SAR controls the incoming feeder breaker and the other downstream equipment. A typical 25 kV substation (Fig. 11.2) contains a remotely controlled isolation switch which connect the 88 kV transmission lines to the bus, an oil circuit breaker, a step-down transformer, and two isolation switches which allow the equipment to be disconnected for maintenance purposes. The 50 kV substation uses a similar design.[11.3] The 400 kV and 275 kV utility network is used to supply the power to the substations as shown in the schematic diagram of Fig. 11.3.[11.3]

Table 11-1

Extent of Electrification in South Africa at the End of 1975 (Ref. 11.1)

Country, Railway, and Lines Electrified	Length Electrified		Voltage	System of Electrification	Conductor	Year Electrified
	Route Km.	All Track Km.				
South Africa—						
South African Railways—						
Durban - Volksrust - Union including sections via Pinetown, Thornville, Howick line and portion North and South Coast lines	1,239	3,043	3,000	D.C.	O H	1926-75
Ladysmith - Bethlehem - Kroonstad	332	463	3,000	D.C.	O H	1935-72
Glencoe - Vryheid - Hlobane	121	161	3,000	D.C.	O H	1968
Witwatersrand area covering all lines between Welgedag and Welverdiend	450	1,310	3,000	D.C.	O H	1937-75
Welverdiend-Beaconsfield	414	913	3,000	D.C.	O H	1958-74
Kamfersdam - Postmasburg-Hotazel	352	474	3,000	D.C.	O H	1972-75
Potchefstroom - Fochville - Houtheuwel	84	160	3,000	D.C.	O H	1965
Welgedag - Witbank (including Broodsnyersplaas - Ogies)	148	401	3,000	D.C.	O H	1973
Clewer - Witbank - Komatipoort	374	686	3,000	D.C.	O H	1965-74
Germiston-Pretoria West	61	257	3,000	D.C.	O H	1937-72
Pretoria suburban area	49	198	3,000	D.C.	O H	1955-74
Wattles - Vereeniging - Kroonstad including Midway - Vereeniging	240	638	3,000	D.C.	O H	1959-74
Cape Town urban and interurban areas	142	447	3,000	D.C.	O H	1928-75
Bellville - Beaufort West (including Stellenbosch loop)	568	950	3,000	D.C.	O H	1953-75
Hercules - Pretoria North - De Wildt	35	83	3,000	D.C.	O H	1971-74
Gunhull-Kalkvlakte	165	372	3,000	D.C.	O H	1975
Whites-Welkom	26	32	3,000	D.C.	O H	1974
Total	4,800	10,558	..	..	..	..

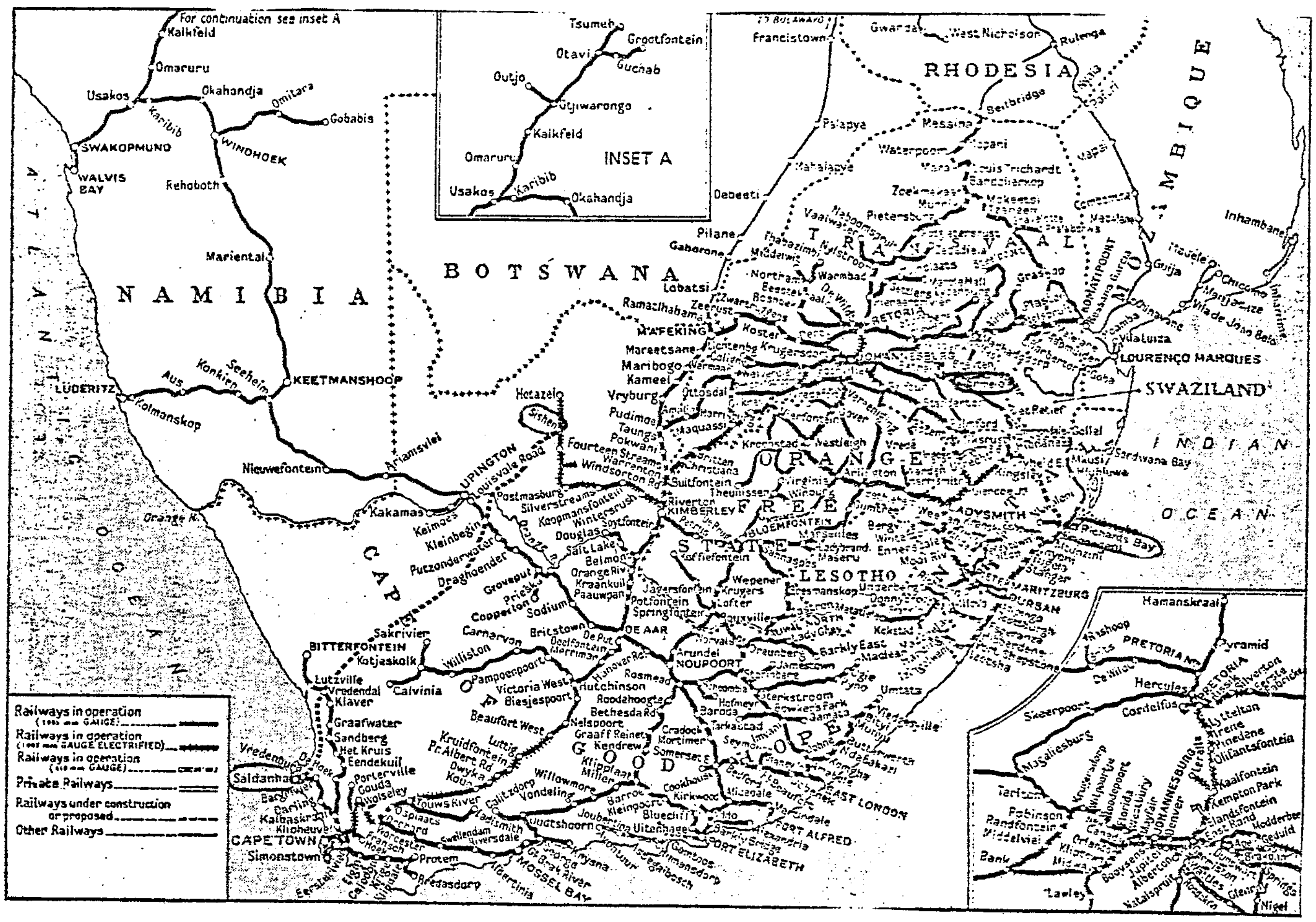


Fig. 11.1 Map Showing Electrification in South Africa as of 1975. (Ref. 11.1)

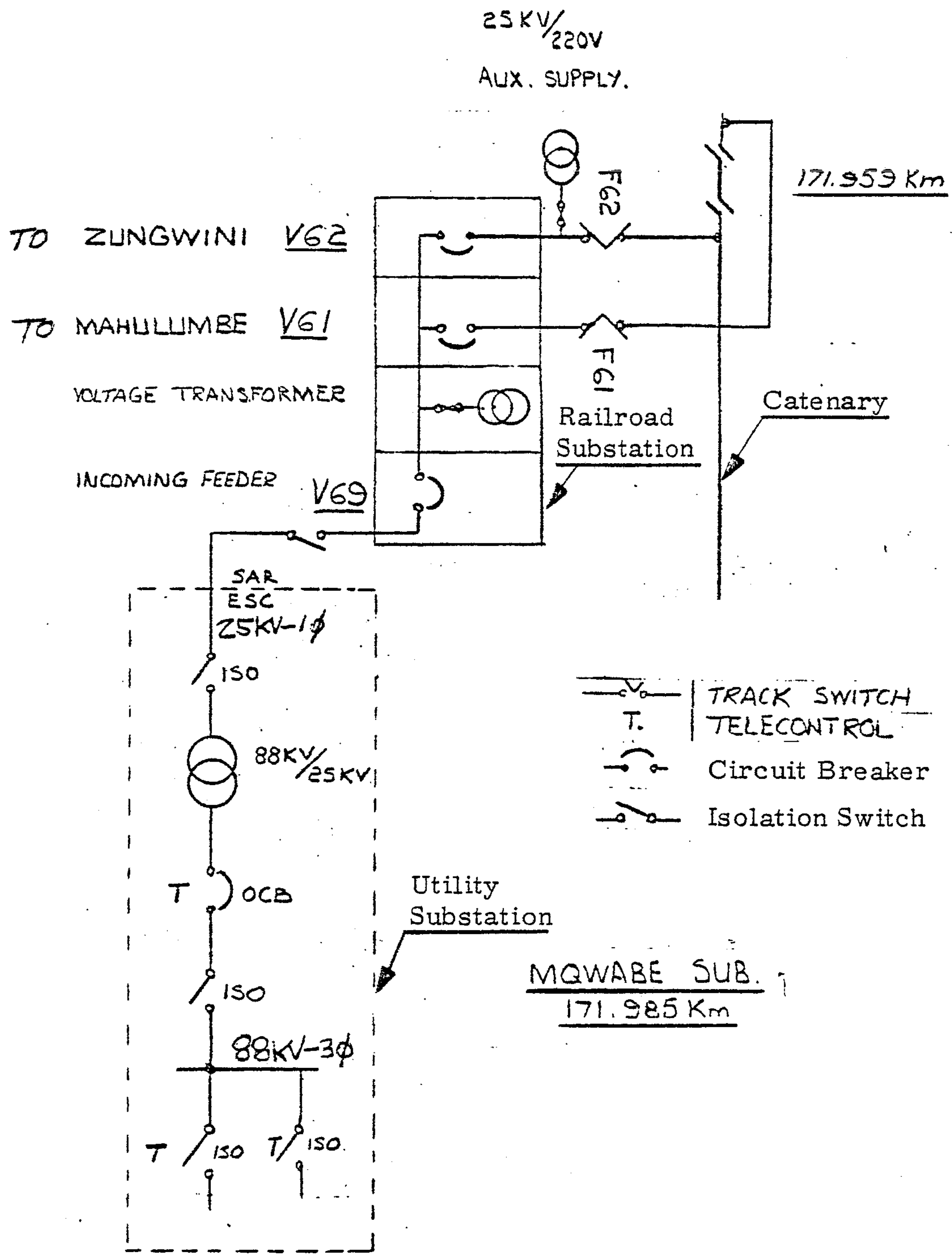


Fig. 11.2 Typical 25 kV Substation Arrangement Showing the Division of Authority Between South African Railways (SAR) and the Electrical Supply Company (ESC). (Ref. 11.3)

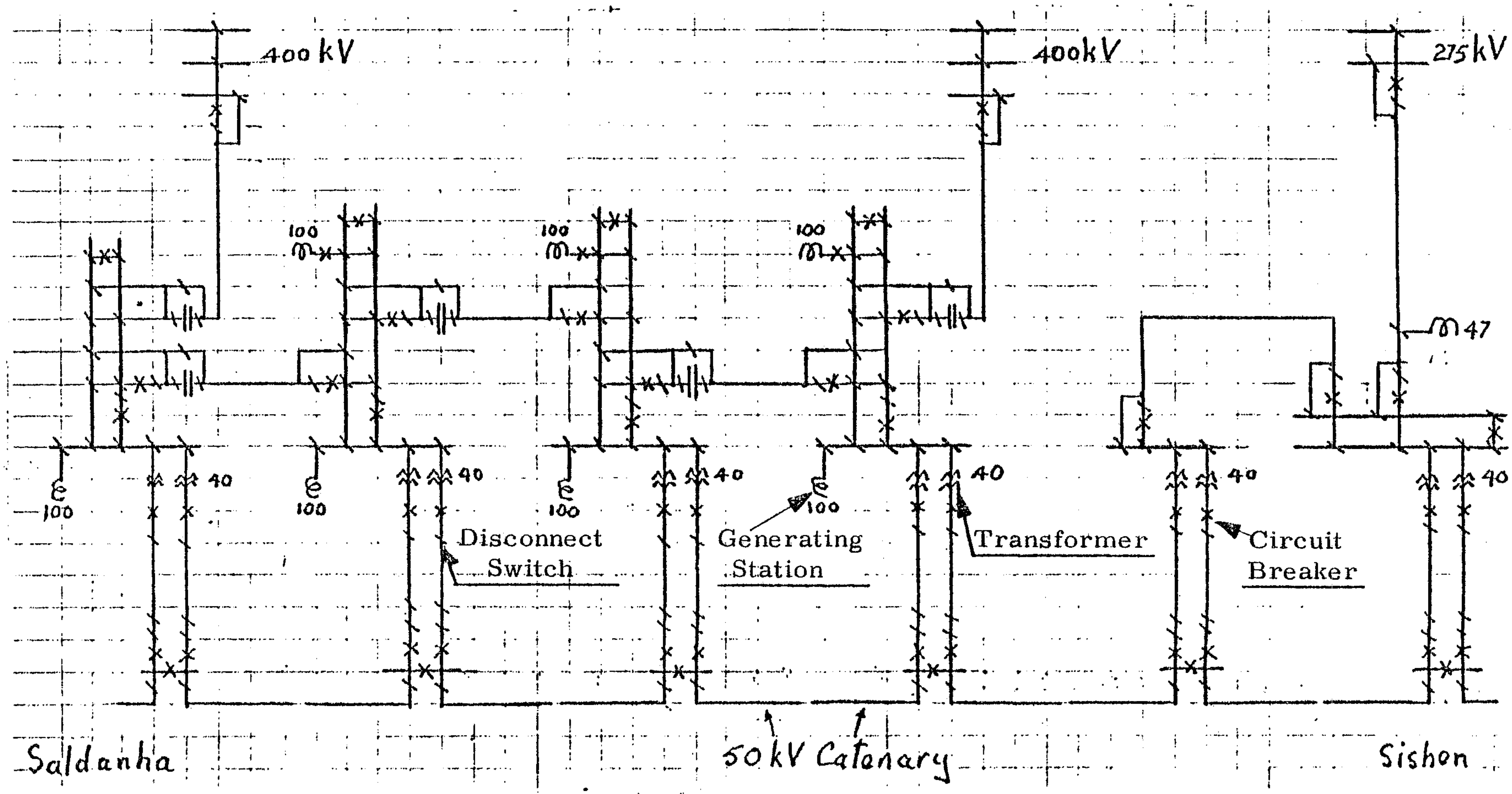


Fig. 11.3 Power System Arrangement for Supplying the 50 kV Catenary Between Sishen and Saldanha. (Ref. 11.5)

11.2 Method of Supplying Catenary

The 25 kV Ermielo-to-Richards Bay line has 14 substations and uses a center-feed system to energize the catenary. Each section of line is protected by its own circuit breaker. Track switches are also available to disconnect the catenary from the substation for maintenance purposes.[11.3, 11.4]

At the design state of the Sishen-to-Saldanha line, Iscor considered several voltage levels before it became apparent that the advantages of a 50 kV system made it the optimum choice for such a sparsely-populated region with few convenient electrical supply points. Based on Iscor's analysis, a 25 kV ac electrification system would have required as many as 24 substations, while the 50 kV ac system selected needs only six. On the other hand, utilization of this high voltage requires larger clearances from adjacent structures, and higher insulation levels.

To provide a secure earth return circuit for the traction current, a return wire is mounted on top of the catenary support poles. This return wire is connected electrically to each pole, and at every sixth pole, an electrical connection between the pole and the running rails is also provided. This should ensure that the voltage step potential along the railway right-of-way will stay within permissible levels. In addition, this arrangement permits adequate multiple low-resistance paths for the return current to travel from the locomotives through the rail and through the return wire to the substations. However, the need for any additional earth connections will be determined during commissioning tests.

The return wire mounted on top of the catenary support poles is expected to provide sufficient protection from lightning, even in inland areas where lightning is experienced an average of 40 days per year.[11.2]

11.3 Track Sectioning Details

On the 25 kV system, neutral sections are placed at substations and midway between substations at track sectioning stations (TSS) (Fig. 11.4). The bus coupler at each TSS is normally open since the system is center-fed, and therefore a voltage phase shift of 120° exists across the neutral section.

A return conductor, used in conjunction with booster transformers as shown in Fig. 11.5, provides a well-defined path for return current in those locations where the earth resistivity is high and electromagnetic interference must be minimized.

The design of 50 kV neutral sections and isolating sections at booster transformer locations presented a particular challenge. Because of the higher clearance requirements for the 50 kV system, the length of these sections required special attention to ensure that no hard spots were introduced into the contact wire. With multiple pantograph operation it is especially important that the pantographs travel from relatively elastic areas into solid areas over adequate transition zones, suitable for the pantograph spacing and speed expected in service.

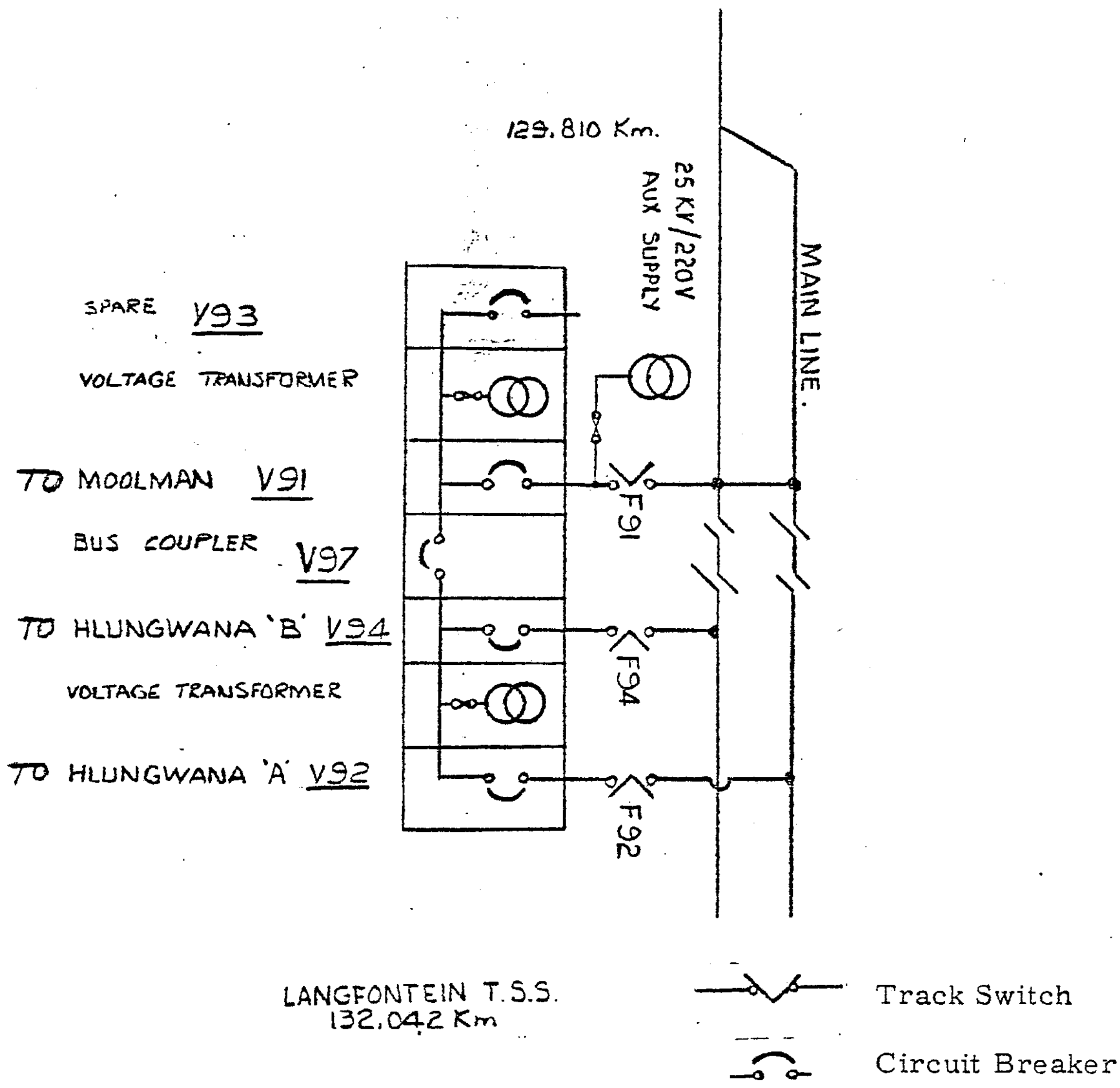


Fig. 11.4 Typical Track Sectioning Station (TSS). (Ref. 11.3)

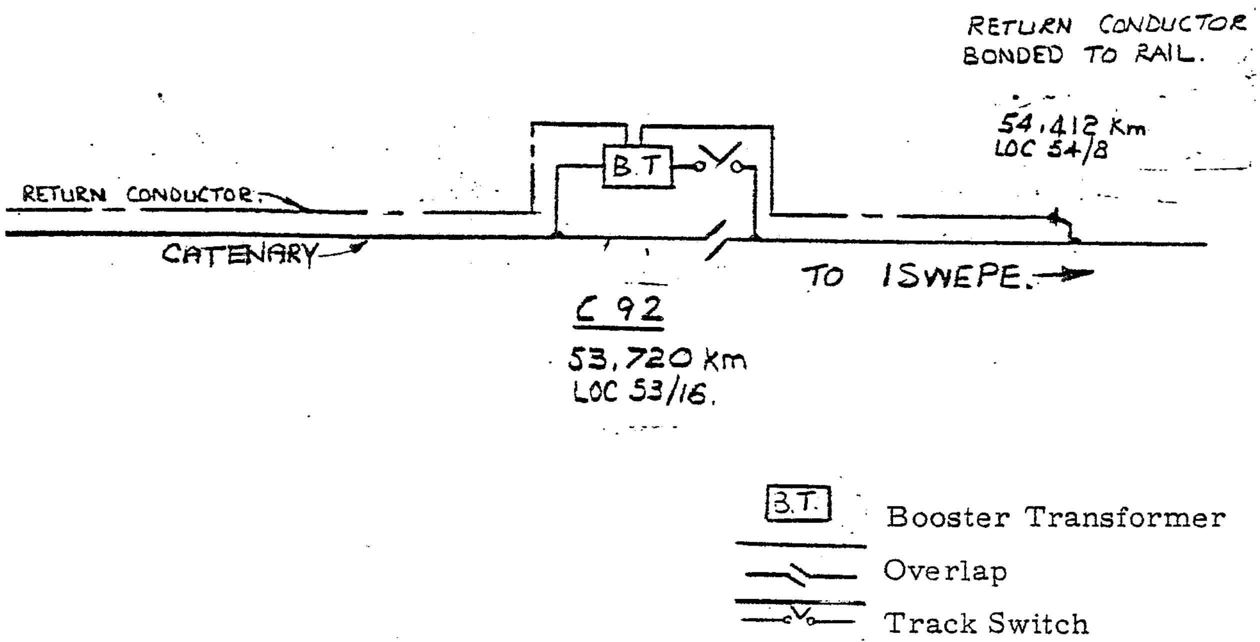


Fig. 11.5 Typical Booster Transformer Arrangement. (Ref. 11.3)

In areas where the potential exists for electrical interference that could degrade operation of communication facilities, booster transformers are installed, and the return wire is carried on insulators on top of the catenary support poles. Connections between the insulated wire and the rails are made at positions which provide for maximum flow of traction return current through the return wire and booster transformer. In this way, a magnetic field opposed to that induced by the current in the catenary is established. This opposing magnetic field reduces the electrical interference due to single-phase electrification to acceptable limits.

11.4 Summary

Recently in South Africa both 25 kV and 50 kV 50 Hz systems have been built. The 25 kV system extends for 200 route-km (1975) and is supplied from the utility's 88 kV network. The 25 kV system is center-fed from seven substations that have one or two transformers per substation. The average spacing between substations is 30 km. The 50 kV system extends for 845 route km, and is fed from six substations with an average spacing of 140 km. This system uses a center-fed catenary. Both systems use booster transformers where needed to reduce interference. Return current wires are used throughout the 50 kV system and those portions of the 25 kV system where booster transformers are present.

11.5 References

11.1 Railway Directory and Yearbook, 1977, Eighty-second year of publication, published by IPC Transport Press Limited, London, England, 1976.

11.2 Siemens, W. H., "Sishen to Saldanha: First Major 50 kV Scheme," Railway Gazette International, September 1977.

11.3 Drawings Entitled "Ermelo-Vryhelo East Schematic Diagram," Drg. No. ECV TT-21, 4 Sheets, April 1978.

11.4 Quail, J.B.; "Considerations in the Design of H.V.A.C. Electrification for South African Railways," presented at the High Voltage Symposium, Johannesburg, 1975.

11.5 Letter to J. J. LaMarca, Alexander Kusko, Inc., from Jan H. Smith, Gen. Mgr., Electricity Supply Commission, Johannesburg, South Africa, dated Dec. 11, 1978.

<u>Additional References</u>

"GEC Provides Motive Power for New Ore Line"; International Railway Journal, May 1978.

12.0 CONCLUSIONS AND RECOMMENDATIONS

In this section, basic numerical information, as well as the similarities between systems, are given for all of the countries with regard to the following criteria: electrification source, feed to catenary, substation redundancy, phasing of substations, and the use of booster transformers, autotransformers and voltage-regulated transformers.

The recommendations suggest additional tasks necessary to complete the work started by this survey report. This report plus the additional tasks will provide useful guidance for electrification programs in the United States.

Conclusions

12.1 Basic Features

The basic features of electrification for each of the ten countries surveyed are shown in Table 12-1. The features include: electrified ac route km, catenary voltage and frequency, transmission voltage and substation spacing. It should be noted that the table contains information for those systems presently in operation. The new proposed systems in the United States are not included.

12.2 Type of Electrification System

In general, two types of electrification systems exist: the dedicated system and the utility-dependent system. The dedicated system operates with a non-standard power frequency (16 2/3 or 25 Hz) and contains substations, transmission lines, converters and,

Table 12-1

Basic Features of the Electrification Systems

in Each Country Surveyed

Country	Electrified AC Route - KM (1977)	Catenary Voltage & Frequency	Transmission Voltage (kV)	Substation Spacing (km)
United Kingdom	1750	25/6.25 kV-50 Hz	132	25-30
France	4500	25 kV - 50 Hz	63, 90, 220	41-67
U.S.S.R.	14900	25 kV - 50 Hz	110	45-50
Japan	4200	20 &25 kV - 50 &60 Hz	220, 270	30-50
W. Germany	9930	15 kV - 16 2/3 Hz	110	60-80
Sweden	7400	15 kV - 16 2/3 Hz	6	*
Switzerland	3500	15 kV - 16 2/3 Hz	66, 132	25-30
Taiwan	540	25 kV - 60 Hz	69	40-50
South Africa	1045	25 &50 kV - 50 Hz	88/132	30 &140
United States	720	11 kV - 25 Hz, 25 &50 kV - 60 Hz	132 138, 230	16 **

* No information available

**Only one substation exists in presently operating systems in some case, generators that are used solely to supply the railroad. The utility-dependent railroad system operates at the power frequency of the local utility (50 or 60 Hz). The substations, transmission lines and power sources which supply the railroad, will in general, also supply the other electrical loads that the utility serves. The Table 12-2 below categorizes the systems by types for the countries studied:

Table 12-2

Type of Electrification Used by the Countries Surveyed

Dedicated System (16 2/3 or 25 Hz)	Utility-Dependent System (50 or 60 Hz)
Federal Republic of Germany	United Kingdom
Sweden	France
Switzerland	USSR
United States	Japan
• Penn Central	Taiwan
• Reading	South Africa
	United States
	• Muskingum
	• Black Mesa & Lake Powell
	• Texas Utilities
	• New Haven (New)
	• Erie Lackawanna (New)
	• Northeast Corridor (New)

12.3 Catenary Feed from Utility

Three different methods of feeding the catenary from the utility network are used by the countries reviewed in this report. These are the center-feed, the single-end-feed and the double-end-feed. The center-feed system exists where power from the substation is supplied at the same phase in both directions of travel, and where the adjacent substations supply power at a different phase. The single-end-feed system is used where power is supplied from a substation at different phases for opposite geographical directions. Separation of track sections occurs at each substation by use of a normally-open phase break. The double-end-feed system exists where power from two adjacent substations is supplied to the catenary at the same phase, so that a train located in the center of the catenary section would receive half of its power from each substation. Table 12-3 categorizes those countries using utility-frequency power by the catenary feed employed:

Table 12-3

Type of Catenary Feed Used by the Countries Surveyed

Center-Feed	Single-End-Feed	Double-End-Feed
United Kingdom	United States	France
	• Erie	
	• New Haven (60 Hz)	
South Africa		USSR
United States		Japan
• New Haven (60 Hz)		Taiwan

12.4 Substation Redundancy

Substations which supply the railroad load are equipped differently. Some substations provide complete redundancy by including two independent supply lines, a spare transformer, and an additional feeder circuit. Others possess only partial redundancy by providing either one or two of the above features. Table 12-4 lists the countries studied as either having complete redundancy or partial redundancy of power supply to the catenary.

Table 12-4

Type of Substation Redundancy Used by Each of the Countries Surveyed

Complete Redundancy	Partial Redundancy
United Kingdom	United Kingdom
France	Sweden
Japan	South Africa
W. Germany	United States
Switzerland	• Muskingum
Taiwan	• BM&LP
United States	• New Haven
• 11 kV 25 Hz	

12.5 Phasing of Substations

The railroads which are supplied directly from a utility power network have either a 120° phase shift or a 90° phase shift across a phase break. A 120° phase shift occurs if power is supplied through a standard single-phase transformer; a 90° phase shift occurs if power is supplied through a Scott-connected or a modified Wood bridge connected transformer. Table 12-5 below shows where each of these phase shifts is in use:

Table 12-5

Phase Shift Across the Phase Breaks in the Countries Surveyed

120° Phase Shift	90° Phase Shift
United Kingdom	Japan
France	Taiwan
USSR	United States
South Africa	• New Haven (60 Hz)*
United States	
• Erie Lackawanna (60 Hz)	
• New Haven (60 Hz)*	
• Northeast Corridor (60 Hz)	

*The phase break at Cos Cob has a 90° phase shift while the other two phase breaks have a 120° phase shift.

12.6 Booster Transformers

Booster transformers are used by some countries to reduce the earth return currents. The electromagnetic interference (EMI) induced by these earth currents often degrades performance of communications equipment. The booster transformer insures that most of the return current passes through the rails or through a separate return wire attached to the rails at many locations, thereby minimizing EMI. The countries which use booster transformers are listed in Table 12-6.

Table 12-6

Countries Surveyed That Use Booster Transformers

United Kingdom
USSR
Japan
Sweden
South Africa

12.7 Autotransformers

Autotransformers are used by some countries to allow substations to be spaced further apart, while still obtaining the EMI reductions of the booster transformer. This is accomplished by using twice the catenary-to-rail voltage between the catenary and an additional feeder, which allows the catenary to supply as much as twice the power to the locomotive. The feeder and catenary are connected to the ends of the autotransformers located along the wayside, while the center tap of the autotransformer is connected to the rail. The return feeder reduces the impedance and minimizes the earth return currents that cause EMI problems. The countries which use autotransformers are listed in Table 12-7.

Table 12-7

Countries Surveyed that Use Autotransformers

France

Japan

USSR*

United States

- New Haven (25 Hz)
- New Haven (60 Hz)
- Erie Lackawanna (60 Hz)

*Planned future use.

12.8 Voltage-Regulated Transformers

Voltage-regulated transformers are used on systems where substations are connected through the catenary (double-end-feed). They serve the purpose of minimizing the current flowing between substations, which is caused by small voltage and phase differences of the utility-supplied power. The railroads are charged by the utilities for these unnecessary currents, which also increase losses to the railroad system while decreasing power factor (more power lag) at the substations.

The surveyed countries which use voltage-regulated transformers are listed in Table 12-8.

Table 12-8

Countries Surveyed Which Use Voltage-Regulated Transformers

France
Switzerland

Recommendations

12.9 Further Work

It is recommended that further work be performed using this survey as the basis to evaluate electrification systems for use in North America. To accomplish this recommendation the following two tasks are necessary:

- First, conduct an analysis of the systems used in the United Kingdom, France and Japan to evaluate the use of each of these systems in its respective country, using the following criteria: geography and terrain; utility network arrangement; railroad construction precedents; traffic density; date of construction; reliability/flexibility of operations; and domestic railroad industry. The conclusions should state the reasons for the design selections regarding substation spacing, method of connection to the utility, use of booster and autotransformers, phase break arrangements and protection details.

- Second, using the results of the study of world-wide electrification practices, conduct an evaluation of selected electrification systems with regard to operations on North American Railroads.

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JL:rm
TSC-1452-3

APPENDIX A

Modified Wood-bridge Transformer Connection

The modified Wood-bridge transformer was developed in Japan for use with their direct-grounded super high-tension network. This special transformer was required for the application because the primary three-phase winding had to be grounded and the secondary winding had to provide a two-phase output for the railroad supply. As in the case of the Scott-connected transformer, a balanced load on the two-phase secondary produces a balanced three-phase load on the utility network.

The diagram provided in Fig. A.1 illustrates the modified Wood-bridge-connected transformer in the dashed area. The primary winding is constructed as a grounded wye and in Japan has a nominal voltage of 275 kV line-to-line. The secondary winding is constructed with two delta-connected windings which are connected across one phase. The voltage magnitude of this common phase, (Phase B), is $1/\sqrt{3}$ less than the voltage across Phase A. An autotransformer is then used as part of the modified Wood-bridge connection (in dashed area) to step up this voltage by $\sqrt{3}$ to equalize the two output voltages. By phasor analysis using Fig. A.2 it is shown that the output voltages have a 90° phase shift. It is also noted that the midpoints of Phase A and Phase B are at the same potential when the two phases are equally loaded so that if the midpoint of Phase A were grounded, the midpoint of Phase B could also be grounded without circulating current problems.

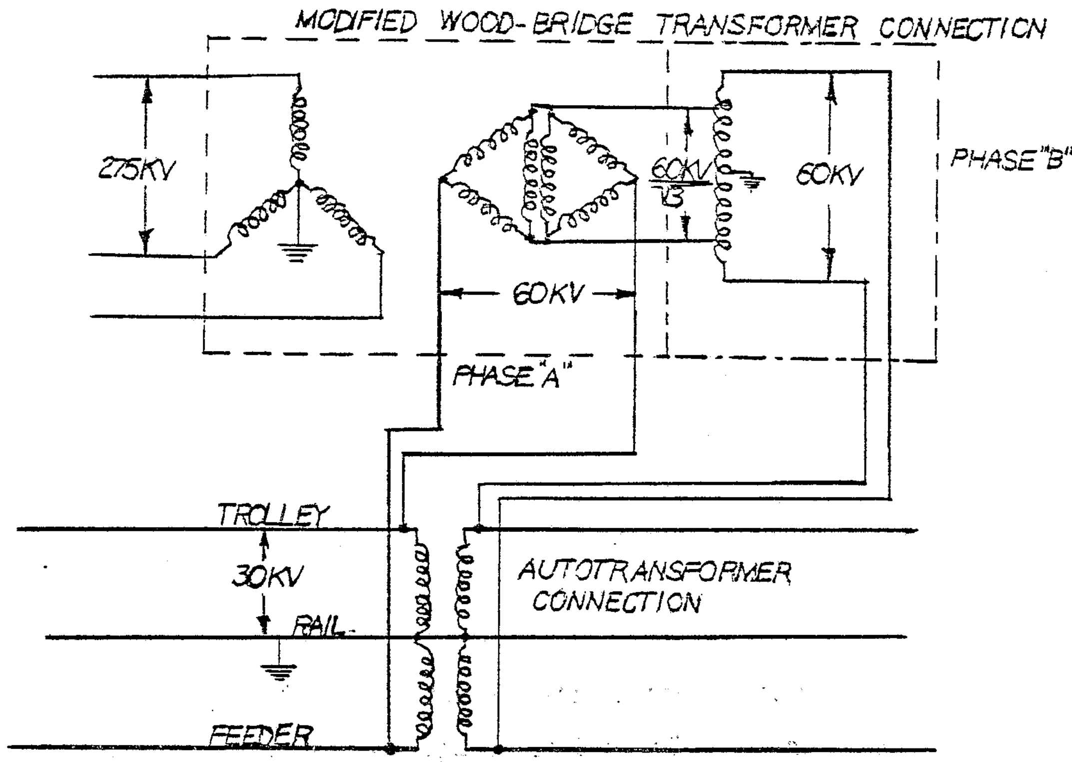

Fig. A.1 Electrical Schematic Diagram of a Railroad Supply Connection in Japan Using the Modified Wood-bridge Transformer in Conjunction with the Autotransformer Feed System.

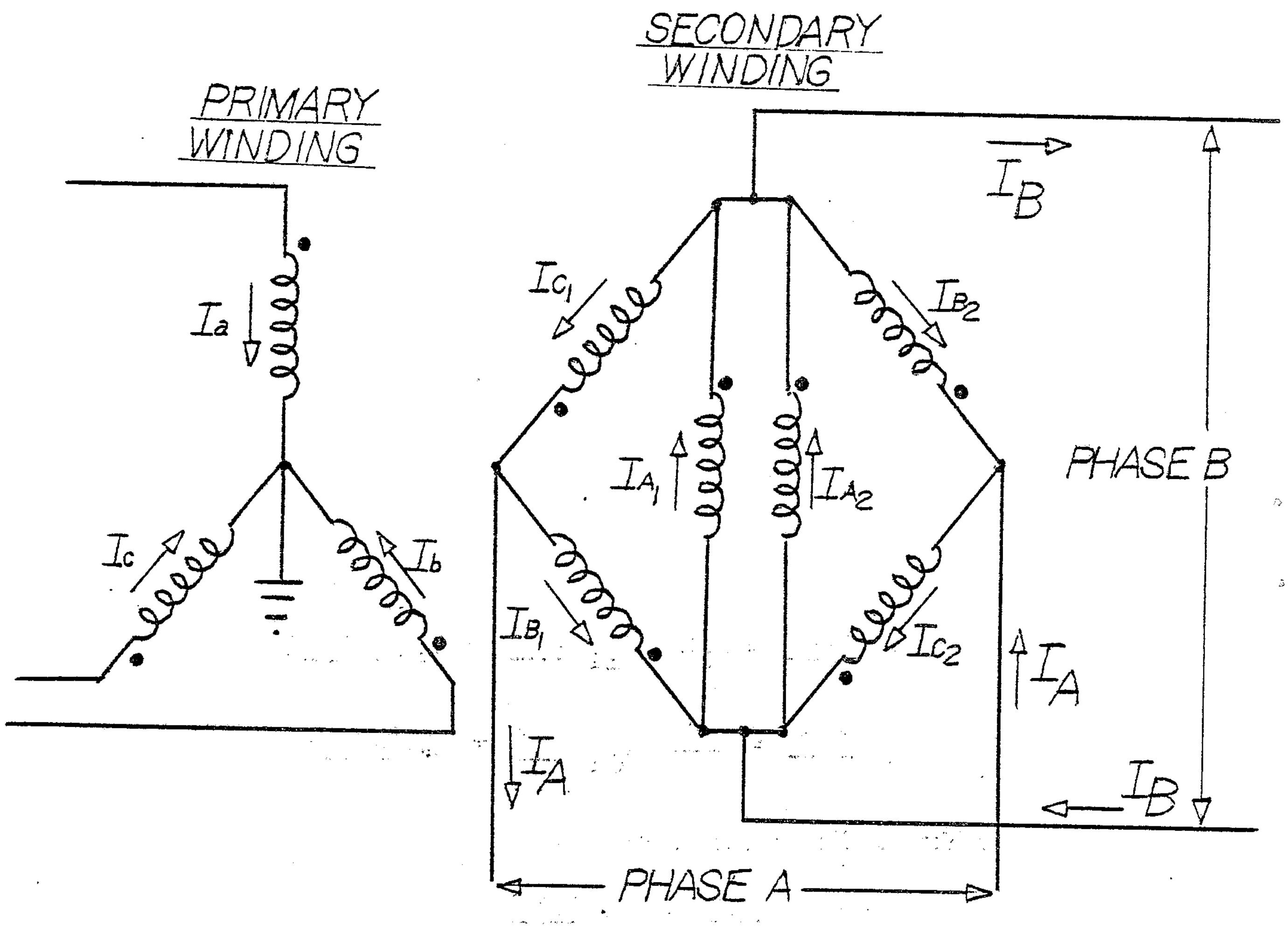

Fig. A.2 Electrical Phasor Diagram of the Phase Shift Portion of the Modified Wood-bridge Transformer Connection.

Analysis

A current analysis is performed using Fig. A.2 and assuming the following:

$$\bar{I}_a = I_a \angle 0^\circ \quad \bar{I}_b = I_b \angle 120^\circ \quad \bar{I}_c = I_c \angle 240^\circ$$

N_1 = primary turns/winding N_2 = secondary turns/winding

Current into the marked end of primary winding results in current out of the marked end of the secondary winding.

The following equations are written for equal magnetomotive force between primary and secondary windings.

$$I_a \angle 0^\circ = \frac{N_2}{N_1}\left(I_{A1} \angle 180^\circ + I_{A2} \angle 180^\circ\right) \qquad \text{A.1}$$

$$I_b \angle 120^\circ = \frac{N_2}{N_1}\left(I_{B1} \angle 300^\circ + I_{B2} \angle 300^\circ\right) \qquad \text{A.2}$$

$$I_c \angle 240^\circ = \frac{N_2}{N_1}\left(I_{C1} \angle 60^\circ + I_{C2} \angle 60^\circ\right) \qquad \text{A.3}$$

Using Kirchoff's current law:

$$I_A = I_{C1} \angle 60^\circ - I_{B1} \angle 300^\circ \qquad \text{A.4}$$

$$I_A = I_{C2} \angle 60^\circ - I_{B2} \angle 300^\circ \qquad \text{A.5}$$

$$I_B = I_{A1} \angle 180^\circ + I_{A2} \angle 180^\circ - I_{B2} \angle 300^\circ - I_{C1} \angle 60^\circ \qquad \text{A.6}$$

$$I_B = I_{A1} \angle 180^\circ + I_{A2} \angle 180^\circ - I_{B1} \angle 300^\circ - I_{C2} \angle 60^\circ \qquad \text{A.7}$$

Adding A.4 and A.5 and substituting terms from A.2 and A.3:

$$I_A = 1/2\, \frac{N_1}{N_2}\left(I_c \angle 240^\circ - I_b \angle 120^\circ\right) \qquad \text{A.8}$$

Adding A. 6 and A. 7 and substituting terms from A. 1, A. 2 and A. 3 :

$$I_B = \frac{N_1}{N_2} \left(I_a \underline{/0^\circ} - 1/2\, I_b \underline{/120^\circ} - 1/2\, I_c \underline{/240^\circ} \right) \qquad \text{A. 9}$$

For balanced conditions $I_a = I_b = I_c$ and therefore A. 8 becomes :

$$I_A = \frac{\sqrt{3}}{2} \frac{N_1}{N_2} I_a \underline{/270^\circ} \qquad \text{A. 10}$$

and A. 9 becomes:

$$I_B = \frac{3}{2} \frac{N_1}{N_2} I_a \underline{/0^\circ} \qquad \text{A. 11}$$

Note that the phase difference between Phase A and Phase B is 90° and that I_B is $\sqrt{3}$ larger than Phase A. The autotransformer on Phase B of Fig. A. 1 decreases the current magnitude and increases the voltage magnitude by a factor of the $\sqrt{3}$.

Similar voltage equations can be written with the results under balanced conditions of:

$$V_A = \sqrt{3} \frac{N_2}{N_1} V_a \underline{/270^\circ} \qquad \text{A. 12}$$

$$V_B = \frac{N_2}{N_1} V_a \underline{/0^\circ} \qquad \text{A. 13}$$