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AC TRACTION SUPPLIES TO BRITISH  
RAIL

Energy Networks Association  
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**A.C. TRACTION SUPPLIES TO BRITISH RAIL****INTRODUCTION**

Subsequent to the publication of this Engineering Recommendation in 1984 it was found necessary to investigate and reconsider the recommendation regarding the levels of nps voltage acceptable on the supply system resulting from the connection of a.c traction loads. As a result of the investigation, revised conditions to be met in limiting the levels of nps voltage are given in this Addendum. A full explanation of the investigations and conclusions leading to this revision is given in Engineering Technical Report 116 "Report on Voltage Unbalance due to British Rail AC Traction Supplies", and this Engineering Recommendation should be read in conjunction with that Report.

**EFFECTS OF NPS VOLTAGES**

The equipment most affected by nps is rotating electrical machines, the predominant effects being rotor and stator heating and the consequential loss of life of the machine. In setting the limits, due account has been taken of the longterm effects on the life of motors and the need to avoid nuisance tripping, whilst keeping motor protection settings at suitable levels to safeguard the machines.

The rationale behind the limits is fully described in Engineering Technical Report 116.

**NPS LIMITS TO BE APPLIED**

In Section 7 of this Recommendation the upper limit of nps voltage is defined as 2% for 1 minute. This has been confirmed by the studies reported in ETR 116 and is determined by machine protection relay characteristics. Since this Recommendation was published, the standard for continuous voltage unbalance which a motor must withstand has been reduced from 2% to 1% so it is undesirable for continuous mean nps levels to exceed 1%.

However, most polyphase machines can withstand nps voltage levels in excess of 2% for short periods although nps voltages above 1% would reduce the machine's life. It is considered that a reduction in machine life of more than 1% would be unacceptable but this does allow some scope for nps voltage levels between 1% and 2%, provided that they are fluctuating (as with BR generated nps) and that they occur only during circuit outages which can be shown to have a strictly limited frequency of occurrence and duration.

It is therefore recommended that the three criteria below be adopted when assessing the likely impact of the railway supply on nps voltage levels.

Although these criteria should strictly be applied at machine terminals this is impracticable so it is normal to calculate nps values and apply the criteria at the lower voltage side (33 kV or similar) of bulk supply transformers. Normally the background level of nps voltage at a 33 kV supply point should be small and hence it has been neglected in the guideline levels. Where a background level exists it may be possible to use it to reduce the level on the system but it is not recommended that this should be used to permit a larger nps voltage contribution from British Rail.

CRITERION	MAXIMUM NPS VOLTAGE LEVEL (at secondary side of bulk supply transformer)	OPERATING CONDITIONS FOR WHICH CRITERION MUST BE MET
1	2.0% for any 1-minute period	Worst BR and/or EI single or two-circuit outage (*)
2	1.0% averaged over any ½ hour period	Intact system
3	1.0% averaged over 24 hour period	Worst BR or EI single circuit outage

\* Normally two-circuit outage conditions would give worse nps levels than single-circuit outages. However, for two-circuit outages BR may be prepared to accept operating restrictions to limit the peak current and hence nps voltage. The effect of this may be included in any assessment of whether criterion 1 is met.

In that case care must be taken to check that single-circuit Outage conditions do not give higher nps levels than two-circuit outages with operating restrictions applied. It should be appreciated that these operating restrictions would not significantly affect the total energy demand and hence would not limit the average nps levels which will be raised as a result of the circuit outages.

ETR 116 shows that for nearly all situations the cumulative effect of nps during single and two-circuit outages is unlikely to result in a 1% reduction in the life of the affected rotating machines. For any one supply point there are normally only a few outages that will result in a significant increase in nps voltage level and the total duration of these outages is small in relation to the normal life of a machine. Therefore, if the three criteria above are met a loss of life calculation will not normally be required. However, if there is a situation where more frequent or lengthy outages are to be expected and especially if nps levels are high, then the analysis technique described in ETR 116 can be used to assess the likely effect on machine life.

A flow chart showing a logical method by which the unbalance voltages produced by a railway supply point can be assessed against the above criteria is shown in Fig 1.

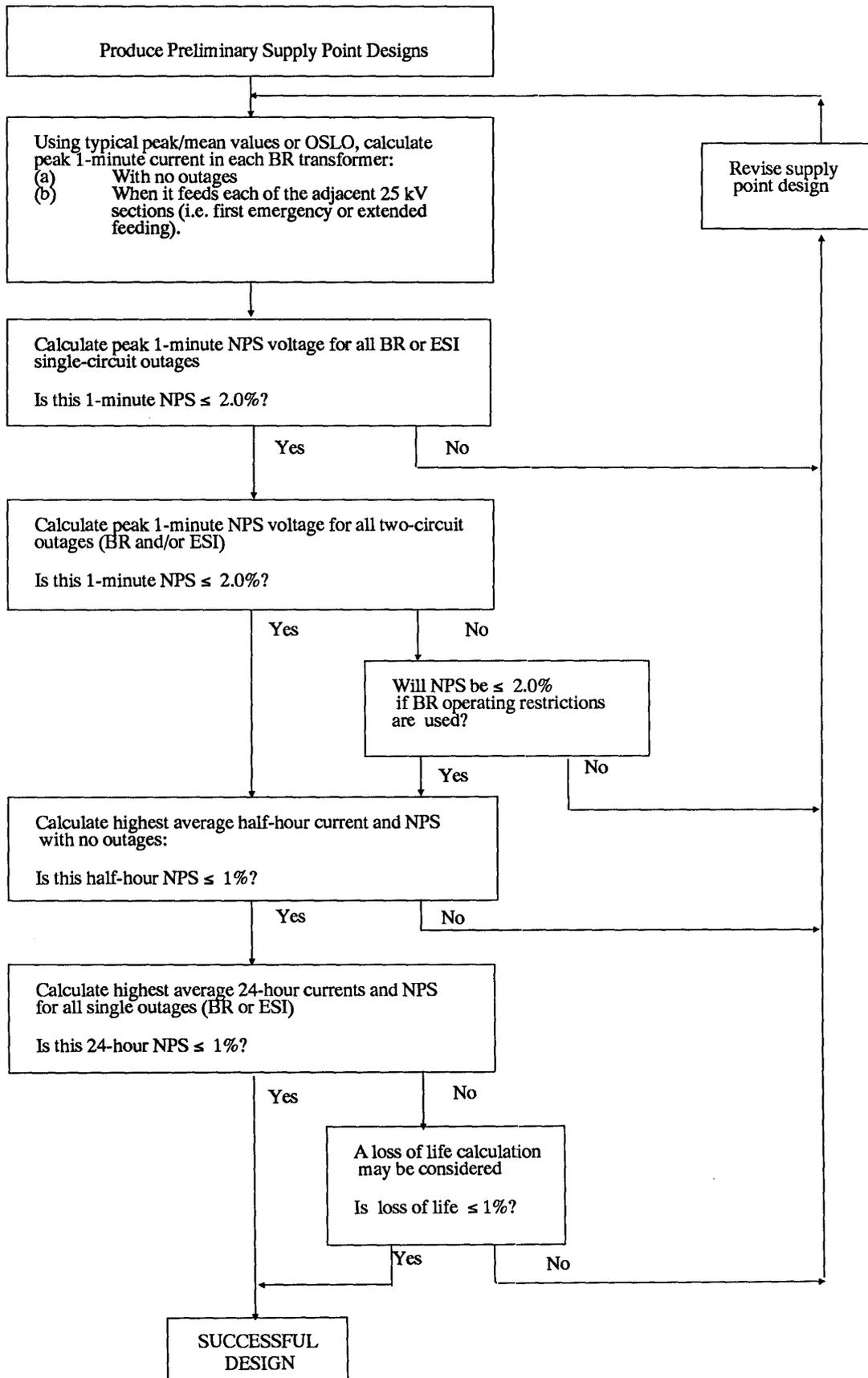


Fig.1 Flow chart showing process for checking NPS voltages

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## A.C. TRACTION SUPPLIES TO BRITISH RAIL

### 1 INTRODUCTION

Electric traction has been employed on railways in Britain since the 1890's with both a.c. and d.c. systems in service. In 1956 British Rail adopted high voltage 50 Hz a.c. as the standard for new electrification schemes. Since that time the West Coast Main Line (Euston-Birmingham-Manchester-Liverpool-Glasgow) has been electrified on this system together with suburban services in Glasgow and out of London Termini (Liverpool St., Fenchurch St., King's Cross, Moorgate and St Pancras). During this major electrification exercise a considerable amount of experience has been acquired, much of which now forms the established practice for a.c. railway supplies in this country. This experience has shown that a line voltage of 25 kV a.c. can now be adopted wherever overhead electrification is physically practicable. Those earlier schemes which originally used 6.25 kV on sections with electrical clearance problems have mostly been converted to utilize 25 kV throughout and the remainder are firmly planned for conversion to the standard 25 kV a.c. system.

With the continuing interest in a.c. railway electrification, it is appropriate that the experience obtained should be presented in the form of guidelines for good engineering practice. Consequently in 1980 the Chief Engineers' Conference approved the establishment of a Working Party of representatives of the Railways and Supply Authorities to prepare an Engineering Recommendation for the technical aspects of 25 kV a.c. supplies to British Rail. This present document is the result of discussions at the working party and recommends the practice for all new installations.

#### 1.1 Supporting Documentation

Throughout this document reference is made to a number of other Engineering Recommendations and design specifications. The references quoted are those relevant at the time of publication but they are subject to periodic revision and readers are advised to ensure that they make use of the most recent version.

#### 1.2 British Rail Terminology

Since a number of the terms used by British Rail in describing their system and equipment items are different from those in general use in the supply industry, the following list has been prepared. This only includes those items where there is no Supply Industry equivalent or the terminology is different and where they may be used in describing the traction supply system.

Automatic Power Control (APC)	Means whereby (i) the electric power circuits on the rolling stock are automatically switched OFF before a train enters a neutral section;
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- (ii) the rolling stock transformer connections are automatically selected according to the voltage of the overhead line equipment;
- (iii) the electric power circuits on the rolling stock are automatically switched ON after a train leaves a neutral section.

APC Track  
Inductor

A magnet fixed on the sleeper ends before and after a neutral section which operates the Automatic Power Control system on the train.

Bond

An electrical connection in the return circuit, or in a track circuit used for signalling.

*Continuity Bond (Traction)*

A bond across the gap in the traction return rails at points and crossings.

*Cross Bond (Traction)*

A bond between the traction return rails of the same or adjacent tracks.

*Impedance Bond*

A device which, whilst allowing the traction return current to flow freely, so impedes the flow of track circuit signalling current as virtually to isolate two track circuits one from another.

*Rail Joint Bond*

A bond across the joint between two running rails.

*Structure Bond*

A bond connecting the steelwork of an overhead line equipment structure, or bridge, or other metal structure, to a traction return rail.

*Transposition Bond (Traction)*

A bond to connect two traction return rails where the traction return rail changes from one side of the track to the other.

Booster  
Transformer

A device to induce into the traction return rails, or return conductors where provided, virtually the whole of the traction return current, in order to reduce to a minimum any interference with communication circuits.

Contact  
Wire

A bare solid conductor being the lowermost of the wires forming the overhead line equipment. The pantographs of electric trains press against the underside of this wire and collect the electric current required by the trains.

Electric  
Locomotive

A hauling unit (for hauling coaching or freight stock, but not carrying passengers or freight) on which the electric motors for the movement

of the train, the associated switchgear, and other equipment but no prime mover, are mounted, and having one or two cabs containing apparatus for driving.

Electric Multiple-Unit	Two or more vehicles coupled together and not normally uncoupled in service, having a driving cab at each end, and including a motor coach.
Electric Multiple-Unit Train	One multiple-unit, or two or more multiple-units coupled together to form one train, and controlled from one driving cab.
Electric Train	A train of coaching or freight stock worked by one or more electric locomotives; single or coupled electric locomotives; or an electric multiple-unit train.
Feeder Station	A building or compound containing electrical switchgear and equipment to which main 25 kV supplies from the Supply Authority are brought, and from which the overhead line equipment is fed.
Isolated	Electrical equipment is isolated when it is disconnected from all sources by which it can become alive.
Neutral Section	An arrangement of wires and insulators including a length of earthed contact wire introduced into the overhead line equipment and designed to ensure that two sections, which must not be connected electrically, are kept electrically separate even during the passage of the pantographs of electric trains.
Overhead Line Equipment	<p>An arrangement of wires, suspended over the railway line, for supplying electricity to electric trains, together with the associated fittings, insulators, and other attachments, by means of which the wires are suspended or registered in position.</p> <p>The whole of the electric track equipment with its structures, foundations, etc., may collectively be described as "overhead line equipment."</p>
Overlap	An overlapping of the ends of two lengths of overhead line equipment; arranged in such a manner that the pantographs of electric trains can pass smoothly and without break of contact from one contact wire to the next over the same line.
Pantograph	A retractable frame, mounted on insulators on the roof of electric multiple-unit trains and electric locomotives, which presses against the underside of the contact wire, and through which the electric current is collected from the overhead line equipment.
Return Conductor	A conductor attached to the overhead line equipment supporting structures, generally at the side of the track, and which carries traction

return current. When used in conjunction with booster transformers the conductor is carried on insulators. At certain places it is sheathed with insulating material but, apart from these places, it is bare. When used without booster transformers it is in electrical contact with the structures and also fulfils the function of an earth wire.

Section	A length of overhead line equipment between a feeder station and a track sectioning cabin, or between adjacent track sectioning cabins.
Supply Return Conductor	A conductor between the grid supply transformer and the return current busbar at the feeder station.
Track Circuit	An electrical circuit formed partly by the running rails and employed for indicating the presence of trains and for controlling signalling.
Track Sectioning Cabin	A building containing electrical switchgear and equipment which is arranged to connect together a number of sections of overhead line equipment.
Traction Return Rail	A designated running rail, carrying traction return current and to which traction and structure bonds are connected. It is also connected to the return current busbar at every feeder station and track sectioning cabin.
Transforming Station	The site containing the supply authority transformers.

## 2 RAILWAY SYSTEMS

Supplies for the railway 25 kV system are usually provided at intervals of between 40 and 60 km. This range of spacing generally meets the railway requirements of which the overriding constraint is normally the voltage regulation on the 25 kV system under emergency feeding conditions. As the security of supply to British Rail is of paramount importance to the reliability of the traction system as a whole, it is normal for a two-circuit supply to be provided to British Rail at each supply point. Each of these two circuits is capable of carrying the total traction load of the supply point for normal railway traffic operating conditions.

### 2.1 Railway 25 kV System Feeding Arrangements

A typical 25 kV system outgoing circuit configuration is shown in Figure 1 25 kV single-phase supplies are received by British Rail at railway feeder stations from which they are distributed to the railway overhead line equipment. Each incoming supply has its own circuit breaker on the feeder station 25 kV busbar, which is usually equipped with a bus-section circuit breaker. Where a neutral section is not required in the railway overhead line equipment, e.g. at the end of an electrified line, a bus-section switch is not provided. From this 25 kV busbar, feeds are given to the railway overhead line equipment through track feeder circuit breakers. These are arranged to provide separate feeds for each main railway

track in each geographical direction. Thus four track-feeder circuit breakers are provided for a two-track railway.

Under normal conditions each feeder station feeds to a mid-point track sectioning cabin (MPTSC) in each direction, these being situated about half-way between adjacent feeder stations. MPTSCs are physically and electrically similar to the feeder stations, with the exception that incoming circuit breakers are not required. Bus-section circuit breakers are always provided at MPTSCs. The MPTSCs perform an electrical sectioning and paralleling function for the 25 kV system. Further sectioning and paralleling of the railway overhead line equipment is provided by intermediate track sectioning cabins (ITSC) situated about half-way between a feeder station and its adjacent MPTSCs. ITSCs are physically and electrically similar to MPTSCs except that bus-section circuit breakers are not provided.

It will be seen from Figure 1 that the sectioning facilities provided by each bus-section circuit breaker normally require corresponding sectioning facilities in the 25 kV overhead line equipment. This facility is given by the provision of a neutral section in the overhead line equipment for each railway track. For feeder stations at the end of an electrified line, neutral sections may not be provided where only one transformer is in circuit at a time or where two of the smaller (e.g. 10 MVA) transformers may be operated in parallel. Also, neutral sections may not be provided at all single-circuit feeder stations.

### **2.1.1 Normal Operation**

Under normal feeding, the supply for the section of railway between MPTSCs on either side of a feeder station comes from the transforming station associated with that feeder station.

At feeder stations with two incoming supplies via larger transformers, the bus-section breaker is normally open and each transformer therefore feeds the section from feeder station to adjacent MPTSC single-ended. This arrangement restricts the 25 kV system fault level to 6 kA in order to avoid undue interference and high voltages to earth on trackside signalling and telecommunications equipment under fault conditions. Provided the phase relationships are correct, the two incoming supplies may be paralleled for short periods of time to maintain a supply during changeover periods when one incoming circuit is to be taken out of, or restored to, service. To cater for such a condition the 25 kV switchgear is rated at 12 kA.

Smaller transformers (i.e. 10 MVA or less) can be operated in parallel, provided the phasing is the same, within the permitted 25 kV system fault level. In this case, and also where there is only one transformer, the bus-section circuit breaker is closed under normal operation.

### **2.1.2 Emergency Operation**

With a single-circuit outage at a two-circuit supply point, the 25 kV supply to the overhead line equipment is maintained by closing the bus-section circuit breaker. This is designated by British Rail as "first emergency feeding" and under these conditions there should be no effect on train operations.

The complete loss of supply to a feeder station is designated by British Rail as "second emergency feeding" and in this case there may be some effect on train operations. This condition will arise from a double-circuit outage of a two-circuit supply point or a single-circuit outage of a single-circuit supply point. In either case the 25 kV supply to the overhead line equipment is maintained by opening the bus-section circuit breaker at the feeder station concerned and closing the bus-section circuit breakers at the adjacent MPTSCs. The feeding lengths of the appropriate transformers at the adjacent supply points are thus effectively doubled, as they feed to the non-supplying feeder station which is now acting as an MPTSC.

### **2.1.3 Electrical Control Arrangements**

All British Rail 25 kV switchgear is under the control of an Electrical Control Operator who is able, by means of a remote supervisory control and indication system, to operate all the circuit breakers, including the incoming feeder circuit breakers at feeder stations, from an Electrical Control Room which is manned on a continuous basis. The operation of all 25 kV circuit breakers in the incoming circuits is subject to the operational limitations of Engineering Recommendation G.38.

The operation of hand-operated disconnectors and earth switches is restricted to authorized personnel working to the instruction of the Electrical Control Operator. The position of all circuit breakers, but not that of hand-operated disconnectors and earth switches, is indicated in the Electrical Control Room and facilities are provided for alarm indications.

## **2.2 Railway 25 kV System Return Circuits**

The traction return rails are bonded to the railway overhead line support structures as well as being cross-bonded at intervals, thereby forming a distributed earthing system typically having an overall resistance to earth of less than one ohm. The traction return rails are directly connected to the feeder station return current busbar.

In the simplest case the current returns to the feeder station return current busbar directly via the traction return rails but this is liable to cause interference in adjacent telecommunications circuits. To minimize this interference it is desirable for the return current to be carried in a return conductor located near to the overhead contact system. To constrain the return current flow in this return conductor, booster transformers having a ratio of 1:1 are connected into each return conductor and its associated 25 kV overhead contact system at approximately 3 km intervals as shown in Figure 2. Return conductors are connected directly to the feeder station return current busbar so that return current in this case can come from the return conductor and/or traction return rails. The return conductors are positioned on the 25 kV overhead line masts in such a position relative to the telecommunications cables as to minimize as far as practicable the induced voltages due to currents in the overhead contact system, return conductor and rails.

### 2.3 Electric Train Characteristics

Each electric locomotive and multiple-unit collects current from the contact wire of the railway overhead line equipment by means of a pantograph which, via a circuit breaker, is connected to the high voltage terminal of the converter transformer primary winding. The other end of the primary winding is arranged to return the current through the wheels of the electric locomotive or multiple-unit to the traction return rail. Usually only one of the running rails of the track concerned is needed for this function, although occasionally both running rails of a track are used for traction return current purposes.

All electric locomotives and multiple-units in service at present on British Rail use d.c. traction motors. For locomotives and multiple-units in service prior to 1979, converters for the d.c. traction supply were solid state rectifiers with voltage control provided by mechanical tap-changers. All traction vehicles delivered to service since 1979 employ thyristor control, usually in a two-stage series-bridge arrangement.

During the period when starting from rest and then accelerating, the input power of an electric train gradually increases from a low value to a maximum, the value of which depends upon the type of traction vehicle and train as well as their operating conditions. A locomotive hauled passenger train typically takes a minimum of one minute before its input power has peaked: for a freight train this period is likely to be of the order of two minutes at least. Multiple-unit trains, which are primarily used on suburban services, take about 30 seconds to reach maximum input power.

The continuous rating of a 4-axle locomotive is of the order of 4 MW and maximum input power normally does not exceed 5 MW but traction units are being developed which could have peak demands of up to 8 MW. Comparative figures for each unit of a multiple-unit train are 1 MW continuous and 2 MW maximum. The train speed at which maximum power is drawn is between a third and a half of the maximum design speed of the train and operation above that speed implies a lower potential instantaneous power demand.

When a train is moving at speed the rate at which the power is re-applied after its reduction due to the observance of signals, speed restrictions or passage through neutral sections, is limited either by the mechanical characteristics of the tap-changer or by an electrical control function in the case of thyristor control. With locomotives the times to regain full power are about 30 seconds for tap-changer control and about 5 seconds for thyristor control. For multiple-unit trains typical times are respectively 10 seconds for tap-changers and 5 seconds for thyristors.

Power on any electric locomotive can be reduced gradually if required to meet changes in traction demand and at the maximum rates implied above for trains moving at speed. With electric multiple-unit trains however there is no facility for a gradual reduction in power - a reduction in power is achieved by switching off and then re-applying power at the new required level. With all traction types, power can be switched off under manual or automatic control at any time and at any level of power demand. This is achieved by opening contactors or circuit breakers or, in the case of thyristor control, by phasing back the thyristor bridges over a period of a few cycles or less.

Although it is technically feasible, British Rail have no traction units in service which are capable of regenerative braking.

### 3 TYPES OF SUPPLY POINT

Although in principle it is possible to connect railway supply points at any voltage between 33 kV and 400 kV the need to limit supply system disturbances usually requires connection at 132 kV or a higher voltage level. The availability of suitable connection points and consideration of cost normally favours connection at 132 kV. Hence the following alternative arrangements are illustrated for 132 kV connection, but the same principles could apply for any other voltage level. The traction supply transformers are single-phase and on the primary side are connected between two phases of the supply authority three-phase system.

Phase pairs are chosen to minimize voltage unbalance. It is recommended that where possible, the three available phase pairs should be used in rotation along the route. This ensures that when a transformer is out of service, the units on either side which are now electrically adjacent, will not be connected to the same phase pair. Normally both transformers at a supply point would be connected across the same pair of phases. However, where it is desirable to reduce further the unbalance or distortion under normal operating conditions there may be some merit in connecting the transformers to different phase pairs. If this is done to make an otherwise unacceptable supply point possible, it would be necessary for British Rail to agree special operating arrangements during first emergency outage conditions. This would involve redistributing some of the traction load onto adjacent supply points and studies should be made at the planning stage to confirm that distortion or unbalance levels at these points would not be exceeded. It would also be necessary to accept the short interruption of supply during a planned outage and to provide electrical interlocking to avoid paralleling the transformers on the 25 kV side.

#### 3.1 H.V. Connections

Where practicable, supplies should be derived from a source which has a level of security not less than that afforded by the provision of duplicate fully rated feeders to the railway 25 kV system. Such a level of security would be given by a sectionalised busbar fed from two circuits, or by two separate busbars each independently fed. The railway transformer feeder circuits would be connected one to each section of busbar but, to economise on h.v. switchgear, each may be banked with other transformers feeding Supply Authority 33 kV or 11 kV networks or consumers. The required degree of security of supply would also be achieved by tee-connecting the railway transformer to separate high voltage circuits - cable or overhead - even though in some cases the two overhead circuits could be on the same double-circuit towers. Figures 3a - 3d illustrate several options which may be adopted depending upon the particular supply point under consideration. These range from transformers switched directly on a busbar, Figure 3a, to a tee-connection to an overhead line, Figure 3b, or a 132 kV cable, Figure 3c, and the situation where a single 132/25 kV unit is selectable to either of two 132 kV overhead circuits, Figure 3d.

Figures 3c and 3d show arrangements of connections with post-type insulators and/or 132 kV cable sealing ends whereby any combination of red, yellow and blue phase relationship may be achieved for the 132/25 kV transformer. The provision of 'swinging' connections is unnecessary if the 132 kV tee-connections can readily be changed as is usually the case with tee-connections from 132 kV busbars, Figure 3a, or where a two-phase tee-connection is made to an overhead line, Figure 3b. The arrangement in Figure 3c is particularly useful

when a 132 kV cable circuit is turned into a transforming station, since not only does it enable a change of phase to be made but also enables the supply to be restored to British Rail in the event of a cable fault between substations B and C. However where single-phase cables are used the cost of diverting all three phases may not be justified. Where a transformer is tee-connected to an existing 132 kV cable circuit, consideration should be given to the possible effect of the single-phase loading on any cable bonding arrangement.

The disconnectors shown in Figures 3b, 3c and 3d are invariably motorised so that the 132 kV circuit can be restored to service following a fault on the 132/25 kV tee-connected circuit. By installing a switching disconnector instead of the conventional motorised disconnector, it may be possible to make a tee-connection which would otherwise be operationally unacceptable.

Figure 3d shows a single 132/25 kV transformer selectable via two switching disconnectors to separate 132 kV circuits. The disconnectors are interlocked so that only one may be closed at any time. An auto-changeover scheme can be incorporated so that in the event of the loss of one 132 kV overhead line, the 132/25 kV transformer can be automatically restored to service from the alternative circuit. This arrangement is preferred to the simple tee-connection when it can be shown that the enhanced security of supply to British Rail is justified either operationally or financially. Where a supply point is teed to an overhead line it should be recognised that overhead line maintenance requirements could require outages of one to two weeks per year. Connection to a switching station would ensure a higher availability due to the shorter maintenance outages. This is an additional consideration to the incidence and duration of fault and repair outages which may be similar for teeing or substation connection.

### 3.2 25 kV Connections

On the secondary side of the railway supply transformers, one terminal is connected to the feeder station 25 kV busbar from which the railway overhead line equipment is fed. The other secondary winding terminal is connected to the feeder station return current busbar to which the traction current is returned from the railway track. To avoid imposing voltages greater than  $\sqrt{3}$  times 25 kV across the bus-section circuit breakers during normal or emergency feeding, the return current busbar must be connected to:

Yellow phase for a red-yellow primary connection

Blue phase for a yellow-blue primary connection

Red phase for a blue-red primary connection

Figures 4a - 4e show the principal connections between the 132/25 kV transformers and British Rail's 25 kV feeder stations for various types of supply point, together with the 25 kV and return current busbars at the feeder stations. It is recommended that whenever possible the arrangement shown in Figure 4a should be adopted. By locating the 132/25 kV substation alongside the railway line, cross-country earth return currents will be minimised.

In the event of being unable to position the 132/25 kV transformers alongside the track, the arrangement shown in Figure 4b is preferred. Figure 4c, with either cable or overhead line between the transforming and feeder stations, shows an alternative arrangement where the

25 kV winding of the transformer is normally left unearthed (see paragraph 11.2 on earthing of the 25 kV system). Figure 4d is similar to Figure 4b but with a 25 kV circuit breaker at the transformer end.

Figure 4e shows a 25 kV overhead line between the transforming and feeder stations and represents a further alternative for separated stations. The high impedance of the return path of overhead circuits, as compared with underground cables, may increase the flow of traction return current via earth and may require the installation of a supply booster transformer in the supply return conductor. Further combinations other than those shown in Figures 4a - 4e are possible; e.g. a 25 kV circuit breaker could be installed on the l.v. side of the grid transformer for the arrangement shown in Figure 4e similar to that shown in Figure 4d, and a supply booster transformer could be included with arrangements in Figures 4b and 4d.

### **3.2.1 25 kV Switchgear**

British Rail has at present standardised on 25 kV single-phase vacuum circuit-breakers, with a rated short-circuit breaking capacity of 12 kA at 25 kV, accordingly the supply authority's 25 kV conductor is similarly switched. The supply return connector is solidly bolted to British Rail's return current busbar.

The circuit disconnecter associated with the vacuum circuit-breaker allows work to be undertaken on the incoming circuit breaker and the associated section of busbar without requiring the operation of any transformer or line disconnecter.

A 25 kV circuit breaker need only be provided at the remote transforming substation (Figure 4d) where:

- (a) the absence of such a circuit breaker to clear faults on the 25 kV circuit between the 132/ 25 kV grid transformer and the feeder station would give rise to an unacceptable risk to the security of supplies to other consumers, connected or teed to the same 132 kV circuit and/ or -
- (b) the establishment of a British Rail supply point by tee-connecting to an existing 132 kV circuit would otherwise contravene the requirements of Engineering Recommendation P.18 (SSEB TDM 13/10001) concerning the complexity of 132 kV circuits.

### **3.2.2 Disconnectors and Associated Earthing Switches**

A 25 kV disconnector of the ganged double-pole type is provided at the supply authority transforming station:

- (a) for isolation of the transformer from the British Rail 25 kV system for maintenance purposes without requiring the operation of any disconnector at the feeder station;

- (b) to ensure that current returning to a transformer still in service (at a two transformer supply point) does not use the supply return conductor of a transformer out of service for maintenance;
- (c) for isolation of the 25 kV circuit between the transforming station and the line disconnector adjacent to the feeder station, without requiring the operation of any disconnector on the high voltage side of the supply transformer.

These disconnectors are fitted with double-pole earthing switches on the line side.

Where the transforming station is remote from the feeder station a 25 kV line disconnector of the ganged double-pole type, fitted with earthing switches on both sides, is provided adjacent to the feeder station. This allows for isolation of the incoming 25 kV cable or overhead line circuit for maintenance purposes without requiring the operation of any disconnector in the feeder station, thereby obviating the need for British Rail personnel presence.

The line disconnector and earthing switches, together with any associated 25 kV cable sealing-ends, may be mounted on a high-level structure at the 25 kV feeder station or alternatively accommodated in a separate fenced compound adjacent to the 25 kV feeder station. Special care is needed with earthing arrangements. Reference should be made to Section 11.

### **3.2.3 Interlocking**

The circuit disconnector associated with the supply authority's 25 kV vacuum circuit breaker in British Rail's feeder station must be interlocked with the circuit breaker such that the disconnector is operable only when the breaker is in the open position. A mechanical key interlock is adequate for this purpose.

Line or transformer disconnectors (IL3 Figures 4a - 4e) associated with the 25 kV vacuum circuit breakers should be fitted with magnetic-bolt interlocks with a.c. coils. The energising supply should be taken from British Rail's a.c. auxiliary supply routed via an auxiliary switch on the associated vacuum circuit breaker and a 1:1 isolation transformer. The insulation between the primary and secondary winding and between each winding and the transformer core, should be rated for 10 kV.

Magnetic-bolt interlocking avoids the necessity for British Rail personnel to attend site to release keys from the vacuum circuit breaker to allow operation of 1L3. The isolation transformer overcomes the problem of insulation breakdown due to differences in potential between equipments in the isolating/sealing-end compound and the 25 kV feeder station at times of primary equipment faults.

### **3.2.4 25 kV Circuit Between the Transforming Station and the Supply Authority Disconnector**

The use of 25 kV underground cable has the advantage that traction return current via earth is much less than for corresponding lengths of overhead line. Concentric cables are always used

because the supply is single-phase. The use of single-core cables would increase the loop impedance (as compared with concentric type) resulting in greater earth return currents and greater sheath circulating current.

Until recent years oil-filled cables with aluminium sheaths were generally chosen. Even with concentric cables, care is needed in earthing or bonding the sheaths to avoid problems due to circulating currents on the two sheaths of a double-circuit supply and to avoid traction return current using the sheath as a partial alternative to the supply return conductor. This aspect is considered in Section 11.

Where a 25 kV double-circuit is made up entirely of metallic sheathed cable, sheath current will be minimal provided there is no bond between the sheaths and British Rail's return current busbar. This is because the difference between the loop impedance (25 kV conductor to earth and sheath return paths) and the loop impedance (25 kV conductor to return conductor) is so great that little current returns via earth and sheath. It also results in the 25 kV and return conductors carrying not dissimilar currents - hence there is no voltage generated to drive current around the two sheaths.

If a short length of double-circuit 25 kV supply is undergrounded, the major portion of the route being formed by overhead line, the supply and return conductors of each cable will carry different currents. Sheath circulating currents may be avoided or minimised by separately earthing the two cable sheaths at one end of the cable route.

The use of polymeric concentric cables, having no metallic sheaths, largely overcomes the above problems, but for safety reasons mainly concerned with the problem of transferred potentials, care is still needed in terminating the cables, particularly at the British Rail feeder station end.

Although an overhead 25 kV circuit can be employed (Figure 4e) the ratio of the loop impedance of the 25 kV conductor/earth return path to that of the 25 kV conductor/return current conductor may not be large enough to prevent a significant proportion of the traction current returning via earth.

Should topographical and/or financial considerations dictate that a 25 kV overhead line be established, traction earth return current can for all practicable purposes be eliminated by the installation of a supply booster transformer (Figure 4e). In carrying out any financial appraisal of overhead line versus underground cable installation, the additional capital cost and capitalised losses of the supply booster transformer should be included in the appraisal.

### **3.2.5 Supply Booster Transformer**

If traction earth return currents are found to be detrimental in any respect, the installation of a supply booster transformer will eliminate the problem. Figures 5, 6 and 7 illustrate in a simplified form the effect on the distribution of traction current in the railway system and the supply connection of introducing booster transformers. When two or more currents (from different sources) are shown flowing in one conductor, the resultant current in that conductor is the algebraic sum, e.g.. the current in the grid transformer earth in Figure 7 is zero. For simplicity, features such as the presence of two or more running rails, return conductors and cross-track bonds and the fact that locomotive current is drawn via TSCs between supply

points, as well as from the nearest feeder station, have been ignored. However, the complications arising from those aspects do not upset the basic theory of current distribution as shown in Figures 5, 6 and 7.

The supply booster transformer is connected differently in Figure 7 from that shown in Figure 4e although electrically the result is the same. The winding connected in the 25 kV line conductor (Figure 7) has simply been removed around through the transformer to give the arrangement shown in Figure 4e. This latter arrangement would be cheaper to manufacture - less insulation required - and easier to connect.

It is recommended that at the planning and design stage, space provision be made in the layout of the 132/25 kV transforming station for a supply booster transformer to be installed at a later date should earth return currents prove to be troublesome. However, if at the planning and design stage evidence is available which shows that earth return currents would be troublesome, the installation of a supply booster transformer as part of the initial equipment should be undertaken or consideration given to adopting the alternative method of system earthing as shown in Figure 4c.

### **3.2.6 A.C. Auxiliary Supplies to 132/25 kV Transforming Stations**

A.C. auxiliary supplies will be required for some or all of the following: disconnector drives, transformer fans and pumps, battery chargers, metering, protective equipments, lighting and heating.

If the 132/25 kV transforming station is on the same site as say 132/33 kV grid transformers, three-phase 415 V a.c. auxiliary supplies will invariably already be available from the auxiliary winding of the earthing transformers.

Should the 132/25 kV transforming station be on a site where no grid transformer auxiliary supplies are available, an auxiliary supply can usually be made available from the Electricity Board distribution network. However, a firm supply cannot always be achieved. If the 132/25 kV supply point is equipped with only one transformer, a single circuit auxiliary supply will usually be adequate. With two 132/25 kV transformers, a firm auxiliary supply may involve the provision of transformers having ratios of 76.2/0.240 kV or 25/0.240 kV. The supply will then be single-phase, consequently single-phase instead of three-phase motors will have to be provided.

If auxiliary supplies are derived from the Electricity Board network comprising distribution, primary and grid substations which are all electrically near to both the 132/25 kV traction supply transformer(s) and the railway line, consideration should be given to the necessity of providing an auxiliary supply isolation transformer sited inside the 132/25 kV transforming station. This would prevent the traction return current flowing from the track via the sheath (sheath and neutral in the case of a PME system) back to the earthed terminal of the 25 kV winding of the 132/25 kV transformer.

Figure 8 shows schematically the arrangement of connections for an auxiliary supply isolation transformer for a three-phase PME system (combined neutral and earth conductor).

Should the 415 V distribution system be of the three-phase four-wire type, the neutral conductor should be left unconnected and insulated in the isolation transformer cable box.

In the event of auxiliary supplies being afforded from an unearthed 11 kV overhead line, there would be no need to provide an isolation transformer subject to the 11/0.415 kV distribution transformer being sited in the 132/25 kV transforming station.

If the 415 V auxiliary supply enters the substation by overhead line an isolation transformer may be necessary in a manner similar to that indicated in Figure 8.

Reference should also be made to sub-paragraph 11.3.2 (d).

## **4 LOAD ESTIMATING**

For any railway electrification scheme, loading calculations including provision for train auxiliary loads are carried out to provide basic data for the study of 25 kV system voltage regulation, equipment ratings and supply system disturbance effects. This section describes the level of information made available to the Supply Authority by British Rail at various stages of an electrification scheme.

The accuracy of projected loading information is only as good as the data available on train schedules and traction characteristics. This basic data is sometimes not firm until after the design stage of a project has commenced and decisions on the location and rating of equipment may well have to be made on preliminary information.

### **4.1 Preliminary Information**

Although the train schedule information is unlikely to be reliable at the initial stage, it is possible to calculate reasonably reliable values of maximum half-hour demands for each proposed transforming station from preliminary data. Knowing the maximum number and types of train likely to be running through an electrical section, the corresponding maximum half-hour demand value can be derived from consideration of train running and the respective rate of energy consumption. The maximum half-hour demand is defined as the average demand over this half-hour period.

Additional information necessary for the rating of equipment can be obtained by comparison with similar existing schemes. The shape of a typical 24-hour load curve such as shown in Figures 9 and 10 for suburban and mainline situation can be fitted to the calculated value of maximum half-hour demand.

In disturbance calculations the traction supply current required is the peak that persists for one minute. An examination of recordings of traction current shows that this peak current is about twice the highest mean current calculated from the highest half-hour demand, assuming a nominal 25 kV and an appropriate power factor. This is based on existing conditions and if trains with higher maximum input power are introduced, as referred to in paragraph 2.3, the peak/mean current ratio will need to be reassessed.

Should the adoption of a peak/mean ratio of 2.0 cause estimated disturbance to equal or exceed the limits, the adoption of any lower ratio than 2.0 should be treated with extreme caution. The speed, operating mode and positions of trains in any electrical track section are extremely difficult, if not impossible, to predict with accuracy.

The current corresponding to either of these demand levels may be derived by assuming nominal voltage, at the busbar, of 25 kV and a power factor depending on load level as described in Section 6.

It is unlikely that the preliminary data will also yield a reliable time relationship between the demands at adjacent transforming stations, still less of those for each supply point over the whole project. By the very nature of railway operations, considerable diversity usually exists between maximum demands at adjacent transforming stations on the same route.

## **4.2 Design Stage**

When reasonably reliable train schedules and traction/train characteristics are available, then 24-hour load curves (on a half-hour demand basis) can be developed for each individual transforming station of a project for both normal and outage conditions. These load curves, being time related, will enable more detailed investigation of disturbance effects on the supply system to be undertaken, should they be required.

## **4.3 Detailed Information**

More detailed loading information can be made available when the train schedule and traction characteristics are known. Computer simulation can output details of loadings on each transforming station against time, either as a continuous plot of r.m.s. current value, or a histogram of current averaged over a chosen period. Typically, the current level is sampled at five-second intervals. Provision of such detailed information would only be necessary where the rating of a particular aspect of equipment or system was considered critical.

## **4.4 Outage Conditions**

Loading calculations are necessary not only for normal feeding conditions but also when one or more outages occur at a transforming station. With normal feeding, loadings will be calculated for each transformer. At transforming stations with two transformers, the loading with one transformer out of service will usually be less than the sum of the maximum demands since these will not be time coincident.

Under emergency feeding with a transforming station completely out of service, the loadings on adjacent transformers will again take into account the diversity between maximum demands and these may be further reduced either by introducing a pre-planned operating restriction on traffic levels or by installing additional sectioning to improve load sharing.

#### 4.5 Timescale

It is normally accepted that a minimum of three years should be allowed for the design, installation and commissioning of a railway transforming station. In practice, every effort is made to give early knowledge of British Rail's long term 25 kV electrification proposals to the Electricity Supply Industry through CEGB Planning Memorandum PLM-SSB-1 or equivalent.

Where the supply commissioning year is taken as Year 0 the ideal timescale for loading information is as shown in Table 1.

#### 4.6 Future Developments

Where the estimated loading is less than the installed capacity of the supply point and the system design study indicates that any of the disturbance levels approach the limiting value, British Rail should be advised that there is no scope for further increase in load at that point without reinforcement of the supply.

Since during the life of the railway system the traction loads may change and the supply system may undergo permanent changes, disturbance levels may increase above the initial values. To guard against complaints from other consumers periodic monitoring of disturbance levels is recommended particularly where transformers are initially scheduled for operation at less than full load.

**TABLE 1 RAILWAY SUPPLY PLANNING TIMETABLE**

Project Year	Loading Information
-20 to -8	Planning Memo PLM-SSB-1 form D. Railway routes planned for electrification. Provisional maximum demands on Area Boards.
-7 to -4	Planning Memo PLM-SSB-1 form C. Projects not yet authorized. Provisional maximum demands on transforming stations described by anticipated general geographic locations.
-3	Authorized Project. Preliminary loading information. Maximum demand on each transformer, typical load curve and maximum/average ratio.
-2	Design information. Confirmation of 24-hour load curves for each transformer under normal and outage conditions
-1	Detailed information based on finalised train schedules and traction characteristics - current/time plots for critical sections.

## 5 STANDARDS OF SECURITY

The following standards of security are applicable to the connection of 25 kV a.c. railway traction supplies only; separate definitions and standards cover d.c. traction supplies. The standards are intended as a guide and should be regarded as the broad minimum, but it is recognised that there may be individual cases where relaxation will be justifiable on economic grounds. However, the consent of British Rail must be obtained before any relaxation of security can be adopted.

The security standards applicable to each supergrid group from which railway supplies are derived should be based on those standards specified in Engineering Recommendation P2/5, the railway demand used being that defined as 'potential maximum demand'. Account should be taken of the fact that in general the railway demand is independent of season and the daily load pattern is repeated throughout the year.

For each particular 275/25 kV, 132/25 kV, 66/25 kV or 33/25 kV transforming station, the following additional standards apply, based on the use of equipment cyclic ratings:

1. The NORMAL MAXIMUM DEMAND is to be met by a railway supply point under normal operating conditions including, in the case of a two-transformer supply point, the loss of one transformer circuit.
2. The POTENTIAL MAXIMUM DEMAND is to be met by a railway supply point under emergency outage conditions resulting from the loss of an adjacent railway supply point.

Figures for the normal maximum demand and potential maximum demand are the maximum half-hour demands to be declared by British Rail as part of their load estimates.

Figure 11 illustrates the demand definitions. In the case of a single transformer supply point there is no firm capacity for a transformer outage and the railway load will be transferred to one or more adjacent supply points. The potential maximum demand could result in unequal loading of transformers at a two-transformer supply point. In this event, British Rail will split the summated potential maximum demand into two components, one for each transformer.

## 6 NATURE OF TRACTION CURRENT

Traction loads fluctuate widely in magnitude and to a lesser extent in phase angle and harmonic content. In order to estimate disturbance to other consumers it is necessary to be able to quantify the form of the load current in a manner which will enable a reasonable estimate of maximum disturbance to be obtained. For this it is necessary to be able to define a representative waveform for the traction load as presented at a supply point. The waveshape will be dependent on the type, number and disposition of the locomotive units as well as the operating conditions i.e. acceleration, normal running, coasting and braking. It will also be influenced by the supply circuit parameters.

## 6.1 Lead Pattern

Measurements have shown that the current taken by a train is not likely to remain constant for as long as 30 seconds. Variations in gradient, curves and wind resistance all require the driver to make frequent adjustments to maintain constant speed. In addition, speed changes will be required to conform with signals and for station stops. Occasionally the locomotive current may change from zero to full load or vice versa in a few seconds and smaller but still quite large changes are occurring all the time. It is clearly not possible to examine in detail all the separate loading conditions and representative patterns must be assumed.

Where a number of trains are travelling on the same track section their currents are combined and Figures 12a and 12b represent typical supply point currents for mainline and suburban routes. Both traces show very large and frequent fluctuations though they are more pronounced on the suburban line.

It is clear that the highest currents only occur for very short periods and have only limited effect on the thermal rating of the supply equipment. Similarly harmonic distortion levels, associated with the peak current levels, may only be maintained for periods as short as 30 seconds. There is at present little guidance on the effect of short duration high harmonic levels and although the thermal effects may not be limiting, the possibility of interference with other equipment may dictate that a short-term peak current level should be used for harmonic injection studies. However, unbalance is likely to be the critical disturbance and as the consequent motor heating effect is not instantaneous the highest one-minute demand is considered to be appropriate. This level can be obtained from detailed load estimates or, as stated in Section 4, from preliminary estimates of maximum half-hour demand and a modifying factor.

Since it is very unlikely that one-minute maximum levels will occur simultaneously on adjacent track sections, it would be appropriate to assume the highest one-minute load on one section and the maximum half-hour demand values for each of the other sections in any interconnected network study.

## 6.2 Current Waveform at Pantograph

As the locomotive drive is from a single-phase converter, the current taken often has a rather rectangular waveform. For a diode rectifier feeding a high inductance load the a.c. supply waveform would be as shown in Figure 13a. When the polarity of the voltage changes the reversal of the current in the transformer takes a finite time due to transformer leakage and supply circuit inductances. During this period, the two diodes involved in the current transfer, impose a short circuit on the supply and the commutation current waveshape is the initial part of the asymmetric fault current; during the remainder of the half-cycle the current may be almost level as shown in Figure 13a.

With the locomotive running at a steady speed such that the back emf of the motor is nearly equal to the effective value of the rectifier voltage the flat topped waveform of Figure 13a is obtained. Whenever the locomotive is starting or when the a.c. voltage is increased to maintain speed on inclines the finite value of the d.c. side inductance results in more rounding of the waveform during the main conduction period as illustrated in Figure 13b. In

practice the frequent changes in required operating conditions referred to in paragraph 6.1 mean that a waveform of the type shown in Figure 13b applies for much of the time. The main variation will be in the peak amplitude and the duration of the commutation overlap angle which will be determined by the loading on the train.

In the future it is expected that an increasing number of trains will have two-series bridge thyristor control. The phase control will be used over its widest range during starting when initially only one bridge is used as in Figure 13c, and the delay angle  $D$  advanced from near  $90^\circ$  towards  $0^\circ$  as speed increases. The second bridge is then brought into use and the waveform appears as in Figure 13d with angle  $D$  again being reduced from near  $90^\circ$  towards  $0^\circ$ . During the final acceleration period and when the locomotive is operating at maximum power the load will be as for the diode case shown in Figure 13a. When operating at reduced power or speed the drive voltage will be reduced by phase control on the upper bridge and for this condition the current demand and hence the harmonic content will be significantly lower.

### 6.3 Current for a Number of Trains

Where a number of trains are operating on the same track section the current at the supply point will be the sum of the individual locomotive currents further modified by the capacitance of the 25 kV supply connection. Figure 14 shows a typical supply current waveform at a feeder station for mainline and suburban situations. The ripple on the current waveform is due to resonance between the capacitance of the overhead line equipment and the source inductance. The ripple observed at the transforming station will be larger if there is cable capacitance between it and the feeder station. Since the capacitance will vary for different sites it is necessary to be able to make a separate estimate to determine the frequency and amplitude of the superimposed ripple as described in Section 8. Hence the diagram also shows a smoothed current curve drawn through the mean of the ripple and this is a fair representation of the sum of the individual locomotive currents. Figure 14 shows little evidence of the flat top characteristic which can be seen sometimes on a single locomotive waveform. The rounding of the waveform is due partly to the effective increase in commutation angle due to the larger current of a number of trains being drawn through the common impedance of the 25 kV connection and the supply transformer. Also, due to the position of the trains on the track and to the fact that the locomotive currents are unlikely to be equal, the overlap angles will be different. However, the most significant factor is the frequency with which operating conditions change which means that at least some of the trains will be accelerating at any one time and hence exhibiting a rounded characteristic during the conduction period.

While it is relatively simple to derive analytically the effective waveshape for a given group of locomotives operating under constant load conditions, the analysis is significantly more complicated if allowance is to be made for one or more locomotives accelerating.

Since the resultant waveshape would be very dependent on the assumed conditions, it is difficult to justify the effort involved. Examination of recorded waveshapes suggest that the one shown in Figure 14 is sufficiently representative for both medium and high load conditions to be adequate for system network studies. The Figure also lists the percentage harmonic content of the smoothed current wave drawn through the ripple signal. In the absence of a more representative waveform for the railway system being examined, this set of

harmonics suitably scaled for the defined loading conditions could be used for network studies of harmonic penetration. This current waveform would only apply for a purely inductive supply circuit and in practice even the pantograph currents exhibit a small ripple due to circuit capacitance. A technique for estimating the effect of the network capacitance on both the equivalent pantograph current and the supply point current is described in Section 8.

If a waveform other than that shown in Figure 14 is adopted, it should be manually smoothed to remove the oscillation due to resonance between the capacitance of the overhead line and the source inductance, in order to make it suitable for use in other network situations. The smoothed waveform should then be subjected to a Fourier analysis taking sufficient ordinates to give an analysis beyond the highest frequency of possible resonance for the traction supply circuits to be examined. It is still possible that ordinate measurement or even aliasing errors will introduce distortion which may be apparent when comparing the waveform obtained, by combining the harmonic components, with the waveform from which the ordinates were measured. If necessary, this difference can most easily be eliminated by applying the set of derived harmonic currents to a purely inductive reactance, using the HARP program, when any residual ripple in the current wave will appear as a magnified voltage ripple. If a smooth curve is drawn through the voltage ripple and the resultant wave harmonically analysed, a revised estimate of the harmonic current can be derived by applying the voltages across the inductive reactance.

#### **6.4 Power Factor**

Power factor is a complicated concept when voltage and current waveforms are distorted. It is preferable to consider only the displacement factor i.e. the cosine of the angle between fundamental voltage and current as used for calculations in this Recommendation.

The process of commutation in the rectifier increases the phase angle between the fundamental current and voltage. Typical displacement angles for the 25 kV load at a supply point range from  $37^\circ$  (0.8 lag) at about 20 MW to  $30^\circ$  (0.87 lag) at 4 MW. Connection of a suitable value of capacitance at 25 kV would be effective in reducing this angle to zero thus minimising the fundamental current loading on the transformer. However even for a unity power factor railway load, since it is connected line-line on the supply network, the currents on the system are leading with respect to one phase voltage and lagging with respect to the other phase involved. The third phase is unaffected. The fluctuating nature of traction current would require rapid changes in the number of capacitors connected for optimum correction. Unlike fundamental currents, harmonic levels would not be reduced by power factor correction, on the contrary they could be increased significantly on both the railway 25 kV and the Supply Authority system by circuit resonances. For these reasons power factor improvement has not been found to be worthwhile in the UK. In some situations the introduction of capacitors may be justified either as part of harmonic filter circuits or for phase balancing and this is discussed in Section 9.

## 6.5 Inrush Current

When a train leaves the zone fed by one feeder station and enters the next section, action is taken which limits the magnitude of the step current picked up by the new section. The driver reduces the current before the transition and taps it up afterwards. However, there is still the sudden connection of a transformer with some remnant flux so that the consequent magnetising inrush current can be appreciable and may take about 2 seconds to decay. In a typical example as shown in Figure 15 the waveform resembles a half-wave rectified current, the harmonic distortion is significant and unlike normal operation contains even-numbered harmonics. However, analysis shows that the maximum harmonic content is equivalent only to about a 10 MVA traction load so that it is not likely to present any serious system problems.

## 6.6 Load Flow Considerations

It may be required to conduct a load flow study on an interconnected supply system feeding both balanced and a.c. traction loads. A simple way uses the HARP program facilities and is illustrated in Figure B5 of Appendix B for another purpose. However, if the more detailed considerations of a sophisticated a.c. load flow study are necessary, then it is possible using a balanced a.c. load flow program three times, once for each phase. Balanced load would be represented in the usual way i.e. the three-phase MVA and power factor, but, for example, all yellow-blue loads would appear in the yellow phase study with an extra 30° lead, in the blue phase study with an extra 30° lag and not at all in the red phase study. Also the traction MVA must be multiplied by  $\sqrt{3}$  to make it compatible with the balanced loads.

## 7 DISTURBANCE LIMITS

The Electricity Supply Industry has issued Engineering Recommendations on limits for various disturbances. They may refer to the maximum from particular types of load or to the maximum levels on the system. Inevitably the advice is under continuous review, and as revised documents are issued from time to time the latest version should be consulted. Engineering Recommendations are not mandatory and special variations and interpretations may well be adopted, particularly if a revision is pending. Table 2 summarises the present position in the UK and it is recommended that the suitability of proposed railway supply points should be assessed against these disturbance limits.

With reference to harmonic levels, the limit at 132 kV may prove to be restrictive and ACE 73 indicates that in certain situations a higher level may be allowed provided the quoted limits at lower system voltage levels are not exceeded.

The unbalance voltage limits quoted in Engineering Recommendation P16 are related to the contributions from the source in question. These have been set at a low level of 1% to ensure that the combination of a number of sources coupled with residual unbalance on the system will not exceed 2% (for one minute as discussed in paragraph 6.1). The limit of 2% is the maximum level allowed on a.c. motors and it would be difficult to guarantee any significantly lower level on a system containing untransposed lines and a number of independent, variable, unbalanced loads.

At the design stage, estimates must be made of the disturbance contribution from the railway supply and this must be added to the existing level on the system. The following guidelines are recommended:

**Unbalance:**

It should be assumed, unless there is clear evidence to the contrary, that the contribution from the new source will add arithmetically to the background level.

**Distortion:**

To obtain the total harmonic distortion from combining background and railway supply harmonics, direct arithmetic addition should be used for the components of the one frequency which will give the highest level. The resultant should then be combined with all the other components as the root of the sum of squares (rss).

**Sudden Voltage Change:**

It may be assumed that there would be no coincidence of the voltage steps due to the railway load and those from other sources.

**TABLE 2 SYSTEM DISTURBANCE LIMITS**

<b>Type of Disturbance</b>	<b>Measurement</b>	<b>Maximum Permissible Value from All Sources</b>	<b>Associated Engineering Recommendations</b>
Unbalance	Negative Phase - Sequence Voltage %	2% for one minute	-
Distortion	Total Harmonic Voltage %	5% at 415 V 4% at 11 kV and 1.5% at 132 kV	G5/3
Sudden Voltage Change	Voltage Change %	1% for Step-changes Increasing Linearly to 3% if Ramped Over 2 s or Longer. Limits Reduced by 25% at 132 kV.	P7/2 P8, P13/1 P16

**8 SYSTEM DISTURBANCE ESTIMATION**

A.C. traction supplies cause unbalance and distortion on the public supply system voltage. Unbalance exists when the fundamental voltage (and hence currents) on each of the three phases are of different amplitude or are not at 120°. Distortion refers to the non-sinusoidal shape of a voltage or current waveform. Due to the single-phase loads presented by British Rail traction supplies the distortion will not be the same on each phase.

For calculation purposes it is necessary to specify the size and shape of the total current waveform at each supply transformer, even though the load continually changes, and then apply these currents to the network.

## **8.1 Study Conditions**

Traction loads are continually varying and in order to limit the total number of network studies, it is necessary to identify those conditions likely to give rise to maximum disturbance. Unbalance and distortion should be considered separately since the conditions for maximum levels may be different.

In general, disturbance levels are likely to be greatest for minimum plant conditions and particular attention should be paid to all credible circuit outage conditions. Similarly outages at railway supply points of the twin or single transformers and the consequent effect on supply point loadings as indicated in Section 5 must be considered.

The load diversity between supply points can critically affect levels of unbalance. The diversity assumed is determined by the detail of the available loading data as described in Section 4. At the early planning stage it is possible that only the highest half-hour average current value will be available for each supply transformer. Although a much higher current can occur for a short time, it would not do so simultaneously at all supply points. An allowance for this is described in Appendix B. Where initial studies indicate that disturbance levels may be unacceptable it may be possible to obtain more detailed information.

### **8.1.1 Unbalanced Loading**

#### **(a) Single Supply Point**

For an isolated supply point, unbalance is proportional to traction load, and the highest load current maintained for one minute should be adopted. If there are two transformers it must be decided whether the peaks on each could be simultaneous or whether less than the peak on one section should be assumed. The assumed currents are added arithmetically if the two transformers are fed from the same pair of phases or for the transformer outage condition, otherwise they must be added vectorially at  $120^\circ$ .

#### **(b) Two or More Supply Points**

To minimize overall unbalance effects on an interconnected supply system, the traction supply points or individual transformers along the route are sequentially connected to phases R-Y, Y-B, B-R, R-Y etc. Unbalance voltages are not then directly proportional to load due to the interaction from adjacent supply points.

If detailed load patterns are available for each supply infeed then a simple tabular procedure will identify the time that should be studied for worst unbalance. The procedure is illustrated in Appendix A, under both normal and supply transformer outage conditions. A more subjective approach has to be used if only the half-hour average power on each infeed is given.

If there is no interaction between supply infeeds, the unbalanced loading at one point cannot influence performance elsewhere and the maximum unbalance at each supply point is found from the ratio of one minute peak load to lowest fault level, see Figure 16. Interaction between supply infeeds may increase or decrease unbalance at a point depending on the nature of the contributions from other parts of the network. An initial assessment of the complete network with peak load at each supply point will indicate where there is significant interaction. The extent and nature of the interaction can be obtained by comparing the study results with estimates for each location considered separately.

If the unbalance shown by the network study is different from that given by the ratio load to fault level, then the traction loads are possibly compensating for each others' unbalance via the supply network and the individual infeed peaks should not have been assumed to occur simultaneously. In this situation, the study result represents extreme optimism and the ratio load/fault level represents extreme pessimism. If the difference, at each supply point, is too wide for a safe judgement to be made, a more realistic estimation of the traction loads must be obtained. If no better information is available on diversity between transformer loads, such as indicated in Section 4, a not unrealistic assumption is that for the feed point being examined, the peak load is taken and at the adjacent infeeds the half-hour average load levels apply.

To find the worst outage conditions at the planning stage requires some judgement for a system having appreciable interconnection. The method described in Appendix A can be followed even where detailed loads are not available. The technique would be to identify the supply transformer that has the highest demand on the pair of phases having the lowest total demand. Assume that that particular supply infeed is lost and that half its peak demand is added to the average at the infeed on either side; all other infeeds being assumed to take their average currents.

### **8.1.2 Harmonic Loading**

Generally, the distortion severity is regarded as being proportional to the total harmonic content of a voltage or current. On this basis the worst cases can be derived as below.

#### **(a) Single Supply Point**

The current waveform assumed per transformer is that which has the greatest harmonic content expressed in amperes. This is normally expected to occur when the load on the supply point is greatest. It makes no difference if there are twin transformers connected to different pairs of phases as one would be assumed to be out of service to calculate the worst harmonics.

#### **(b) Two or More Supply Points**

When there are a number of supply points, experience has shown the worst harmonics are likely to arise from a particular pair of adjacent supply points. It is shown in Appendix A that when two loads connected to different pairs of phases combine, the harmonics do not all combine in the same way. The worst odd triplen harmonics occur when the difference of the

two load levels is highest, but most other harmonics will be highest when the vector sum of the two loads at  $60^\circ$  is a maximum. Hence if detailed load estimates are given then this rule can identify the worst time and place for studies, under normal and outage conditions.

Given only the average currents at the planning stage, the technique adopted to determine worst unbalance, involving a network study may be used. The recommended program (HARP) calculates both unbalance and harmonic distortion simultaneously.

## 8.2 Method of Calculation

Disturbance levels are most conveniently estimated using the familiar single-phase programs but representing all three phases side-by-side. This is described in Appendix B. For this purpose traction load currents on each phase must be broken down into their fundamental and harmonic components. When these current components are injected into the supply network model it gives the voltage drops which will appear as the harmonic and negative phase-sequence components of busbar voltages.

Although, as stated, fundamental currents and voltages are treated in the same way as harmonic quantities, the basic calculation of unbalance and distortion are described separately.

### 8.2.1 Unbalance

The three-phase unbalance for an isolated traction supply is easily calculated. It is the single-phase load, MVA, as a percentage of the three-phase fault level at a given supply busbar. This will be the negative phase-sequence (n.p.s.) voltage as a percentage of nominal phase to neutral voltage (at fundamental frequency) as required in declared limits. Figure 16 illustrates this and derives the simple formula. It can be shown that if there are two single-phase loads connected to different pairs of phases at this supply point then the "load" in the formula for n.p.s. voltage must be the vector sum of the two individual loads at  $120^\circ$ .

Clearly the unbalance would be reduced if there were three similar traction supplies connected to different pairs of phases on a closely interconnected system. However, these in-feeds cannot be at the same point, and it may be found on systems supplying two or more traction loads that unbalance depends less on fault levels than on the n.p.s. voltage drops on the interconnecting lines. A computer study of the system as a whole is therefore necessary.

### 8.2.2 Harmonics

To calculate harmonics on the system, the waveform of each traction supply current must be specified so that load harmonics can be derived. These harmonic currents multiplied by system impedance produce the harmonic voltages which need to be estimated.

In the relatively simple example of a single supply infeed, two phases will be equally affected and the third phase will be unaffected. Hence only one phase condition need be sought and this is done by injecting the given load harmonic current at each frequency in turn. amending

the system reactance to suit. Appendix B shows an illustrated example. In practice there are likely to be two or more supply points connected to different phase pairs. A digital program is then necessary because currents must be injected simultaneously at the various supply points represented in the study.

### **8.2.3 Use of Digital Program**

The CEGB digital program HARP03 (Ref. CS/C/P300) can perform both the unbalance and harmonic calculations. As shown in Appendix B the study should be in stages requiring manual intervention but a new version, HARP04, is now available to automate the process (Ref. CISD/CC/P687).

With modern computing and user facilities, data only needs to be written down once. Thereafter it is merely necessary to specify changes from a previous study. Several studies can therefore be performed easily and quickly to show the effect of any variations in train load or system conditions.

The output of HARP can contain all or any of the following results:

- (i) The fundamental and harmonic levels on each phase for the voltage at any busbar and the current in any line. In addition the n.p.s. components are provided.
- (ii) Harmonic impedance/frequency graph for any busbar.
- (iii) Voltage and current waveforms.

## **8.3 Sources**

### **8.3.1 Traction Load Levels**

The data likely to be available at the planning stage is detailed in Section 4. The estimated demands will be in MW and in converting to MVA for study purposes, the fundamental current should be assumed to lag the fundamental voltage by an appropriate angle, see Figure 14.

### **8.3.2 Traction Harmonic Currents**

In the absence of detailed information, the total current waveshape shown in Figure 14 is fairly typical and may be taken for each track section in planning studies. The amplitude and hence the harmonics relate to a particular MVA load but can be scaled proportionately for other loads without significantly impairing the validity of the overall study.

Since the harmonic composition excludes the superimposed ripple, it effectively represents the summated pantograph currents. This differs from the supply transformer current due to modification by the 25 kV circuit capacitance. As given, injected currents assume a purely

inductive supply system and must be adjusted to allow for the local system resonance, as shown in Appendix B.

### **8.3.3 Supply System Data**

Only the 50 Hz impedances of supply equipment need be quoted. They may be given in the National Data Catalogue. Minimum plant conditions should be assumed; the appropriate circuit arrangements and the generation in service can be ascertained from conventional planning studies.

The transmission system may need to be represented to as far as all busbars having generation that makes a significant contribution to the fault level at the primary of the traction supply transformer.

Distribution systems fed from the point of common coupling with a traction supply need careful representation for harmonic studies. An equivalent network will not be valid for all frequencies. Transformers between say 132 kV and 33 kV should be represented. Similarly, for all the transformers 33 kV/11 kV. Single capacitors at 33 kV and at 11 kV could represent all the capacitance at these voltage levels. Loads would be shunt impedances off 11 kV, or perhaps 33 kV, with whatever detail is available. Power factor correction capacitors should be included. Motors should be represented by their sub-transient reactance and resistance in series. Heating loads can be represented by a resistance. Area Board records will be the source of this distribution data.

### **8.3.4 Railway System**

As total section loads are assumed in studies, only the lumped 25 kV capacitance is normally included. This is typically 0.01 micro F per single track km and British Rail will confirm the total for any given location. To this must be added the capacitance between live and return conductors of any 25 kV line or cable to the feeder station; the Area Board will give details.

## **8.4 Network Voltage Levels**

Occasionally there is a requirement to determine the voltage levels on each phase at a point on the system as a result of the connection of the railway load. This can be obtained using the same three-phase representation as described in Appendix B if a three-phase balanced voltage is applied at the generation source terminals and line-line impedances are included for each traction load. An illustrated example is given in Appendix B. The effect of phase balancing is readily examined using this technique.

## 8.5 25 kV Short-Circuit Level

A fault on the 25 kV system is equivalent to a line-to-line short-circuit on a three-phase system. The fault current is driven through twice the system reactance per phase by the line voltage. The r.m.s. symmetrical fault current calculated in terms of the usual X% values on 100 MVA base is:

$$\text{r.m.s. short-circuit kA} = \frac{10000}{(2X_s + X_t + X_1)25}$$

where  $X_s$  = source reactance to the primary terminals of the railway supply transformer.

$X_t$  = the nameplate % reactance of the transformer multiplied by 100 divided by MVA rating.

$X_1$  = the "go" and "return" reactance of any 25 kV line or cable to the feeder station, plus that of the 25 kV traction system if the fault is along the track.

Values of  $X_1$  for the 25 kV traction system vary but can be derived from the following impedances including booster transformers:

	<i>Ohms per km</i>
Single track	0.276 + j 0.769
Each track of a double track	0.3 + j 0.799
Each outer track of a 4-track	0.283 + j 1.015
Each inner track of a 4-track	0.308 + j 0.868

Multi-track total impedances are:

Double track	0.15 + j 0.4
4-track	0.074 + j 0.231

Multiplying these by 16.0 converts them to % on 100 MVA base as required in the studies.

Observed fault currents have been virtually sinusoidal and constant in amplitude throughout the duration of the fault. There is no appreciable decrement as generator reactances pass from subtransient to synchronous, because the generation reactance is a very small part of the total fault reactance.

The above calculation gives the r.m.s. value of the fault current. However it must be remembered that depending on the voltage at the instant of fault the current could be completely asymmetrical initially. It could take up to four cycles to become symmetrical about the zero axis.

## 9 REDUCTION OF DISTURBANCES

Where studies made at the preliminary design stage (project years -7 to -4 in Table 1) show that the connection of the railway supply point will cause excessive disturbance to the supply system, consideration will have to be given to modifying the design. Selection of an alternative supply point or connection to a higher system voltage level are possible options. Rearrangement of the phase connection for one or more supply points may be beneficial, mainly in respect of the unbalance giving rise to excessive negative phase-sequence (n.p.s.) voltage levels but may also help in reducing harmonic levels in some situations. Where measures of this type are inadequate, consideration may need to be given to the introduction of phase balancing and/or harmonic filtering equipment.

### 9.1 Phase Balancing

Where studies show that the unbalanced nature of the railway supply load is likely, in conjunction with existing system unbalance, to exceed the permissible limit of 2% for any possible operating condition remedial measures must be considered. Where special difficulties are experienced, consideration may be given to provision of phase balancing equipment. This can be useful where system fault level is low and may permit the railway to be supplied from a lower voltage point, e.g. 33 kV provided there is sufficient supply capacity.

Phase balancing may be achieved by connection of suitably proportioned inductors and capacitors across the three phases so that the resultant of their currents and the unbalanced load presents a more balanced three-phase demand on the supply. Further details of the balancing action and the calculation of component values are shown in Appendix C. Figure 17 shows the two basic alternative arrangements for phase balancing as it could be applied to railway supply points provided the controlled elements can be economically designed for direct connection at up to 33 kV. Where thyristors are used as switching elements a much lower voltage would be preferred and a separate transformer would be required for the compensator. Where there is no requirement for a local 33 kV supply the three-phase 132/25 kV transformer should not be significantly more expensive than a single-phase unit for the same rating.

The limiting condition defining the rating of the compensator would be during the outage of a railway supply transformer where two track sections must be fed from the same transformer.

The balancer must limit the unbalance to the specified value which ensures that the level on the local supply system to other consumers does not exceed 2%. If there are two transformers at a supply point some economy in compensator components is possible if both supplies are taken from the same pair of phases. It is not then necessary to provide both capacitive and inductive controlled reactances in each phase since the nature of the unbalance load variation restricts the range of compensation required.

The control system for the phase balancer can be designed to operate only on the load drawn by the railway with the control signals derived from railway load current measurement. Alternatively the system can be designed to attempt to minimise the total unbalance on the local supply system. This requires the compensator to react to the net out-of-balance due to

the railway and other loads. It should in general provide a better quality of supply for other consumers. The control signals would need to be derived from the voltage at the point of common coupling.

Since in either case the total system unbalance is due both to the railway and other loads it will be necessary to agree the amount of compensation to be attributable to the railway supply. This could be a matter for negotiation but it may be appropriate for the n.p.s. contribution from the railway supply to be limited to 1% at the agreed minimum system fault level. Two main types of compensator have been identified as below.

### **9.1.1 Smooth Control of Unbalance**

Where smooth and precise control of unbalance is required equipment including thyristor control of the reactive elements must be used. Current flow in part of the inductive load is switched by back-to-back connected thyristors operating under phase control. This provides a smooth variation of effective inductive reactance value from open circuit to the actual component value. Only part of the total inductive load need be operated under phase control with some duplication for security. The remainder would be in separate units of about the same size switched in by their own back-to-back connected thyristor as required. This has the merit of reducing the harmonic distortion produced by the compensator. The size of the reactor units would be optimized in terms of thyristor and reactor costs.

The capacitor banks are similarly sub-divided but have to be switched in as units since phase control is not applicable. However the fast response-of the thyristors and the associated control allows the phase controlled reactor unit to effectively smooth out voltage changes which might otherwise cause annoyance.

Where the balancer is only required to deal with the railway unbalance the arm connected across the railway phases will be capacitive and by inclusion of suitable inductors can provide harmonic filtering. It should be possible for some of the capacitance to be in circuit at all times and additional capacitance will be inserted as the traction load increases. Hence added filtering will be introduced as it is required by the additional harmonic distortion.

The cost of phase balancing equipment will depend on the degree of sophistication and the connection voltage. For a balancer connected at 25 kV or 33 kV the cost is likely to be in the range 2-3 times the cost of a transformer of the same rating. Operating losses are likely to be of the order of 0.75% of MVA rating but would vary with the operating conditions.

### **9.1.2 Step Control of Unbalance**

Where a less precise control of the unbalance is permissible lumped values of capacitance or inductance can be inserted when required. Vacuum switches would probably be used as the controlling element to reduce maintenance requirements. The sub-division of the reactive units provides some measure of added security against failure of individual sections. The degree of sub-division of the active components determines the number of switching operations and precautions would need to be taken to distribute these between the switches. Discrete component switching would also increase the number of voltage steps applied to the

system, but suitable selection of component value for the individual steps could limit the step voltage to an acceptable level. The maximum voltage step at the point of common coupling should not exceed 1%. For most railway supply points there can be very considerable and rapid fluctuation of traction load as shown in Figure 12. This would necessitate frequent switching and such information should be made available to manufacturers quoting for balancing equipment. While it is possible that the compensator need not respond to load fluctuations of very short duration it must be able to prevent an excursion of the system n.p.s. level beyond the 2% limit for longer than about one minute if operation of sensitive motor protection is to be avoided.

## 9.2 Harmonic Filtering

With railway supplies connected at 132 kV it is normally unnecessary to provide any form of harmonic filtering. However, further extensive railway electrification and a possible general increase in the proportion of distorting load on the system could make it more difficult to keep within the present harmonic limits. Where phase balancing equipment is proposed in order to permit connection at a point of low fault level it is to be expected that distortion will also be a problem and some measure of harmonic filtering could be required.

If harmonic filtering of the railway load is required the equipment could in principle be located at:

- (a) the primary of the locomotive transformer
- (b) the feeder substation
- (c) the secondary of the 132/25 kV railway supply transformer if this is on a separate site
- (d) the primary of the railway supply transformer.

Location of the filters on the locomotives has the merit of reducing the harmonics at source with the possibility of reduced interference in signal circuits from harmonic currents in the overhead contact wire. The capacitance of the filter would compensate for the lagging current demand of the rectifier but under light load conditions the circuit may be overcompensated so that there is little overall benefit in terms of contact wire loading. There would need to be a separate filter on each locomotive rated for the full harmonic output and the accommodation of this equipment could present some problems.

With the filters at the feeder station a single filter unit would deal with all the trains on that section. Since there would be some measure of diversity between the different harmonic sources the overall rating of the filter would be less than that required for the simple arithmetic summation of the maximum requirements for the individual locomotives. However, there is the possibility of increased harmonic current in both the overhead contact wire and the supply return conductor due to an effective reduction of the commutating reactance. The filter capacitance would improve the power factor of the railway load and hence reduce the maximum load and regulation on the supply transformer. However,

consideration would have to be given to the possible rise in 25 kV system voltage under zero or low load conditions.

Location of the filter at the secondary of the railway supply transformer is substantially the same as for location at the feeder station except that the zone over which significant harmonic currents occur is extended beyond the British Rail boundary. This is only different from conditions without a filter to the extent that the inclusion of the filter could increase the level of some harmonics in this zone. This would probably only be a consideration if the 25 kV connection to the feeder station were by overhead line.

Connection of filter circuits on the primary of the railway supply transformer would require the use of a much larger filter bank since it would have to present a lower impedance at harmonic frequencies to divert current away from the low impedance of the supply system. In addition it would draw harmonic currents from any existing distortion on the supply system and would have to be rated accordingly. To be most effective the filter would need to be connected between phases and fully insulated for the high system voltage.

In general, if filtering is required, the preferred location for the equipment would be at the feeder station or marginally less satisfactorily at the 25 kV side of the transforming station. The complexity of the filter would depend on the degree of filtering required but in general separate tuned arms, as shown in Figure 18a, for 3rd and 5th harmonics would probably be required and should be adequate for most situations.

With low frequency filters the fundamental frequency losses in the necessary damping resistances can be large. An alternative to single tuned filters for the lower frequencies is a form of a 3rd-order damped filter known as the C-type filter shown in Figure 18b in which the damping resistance is shunted by a series LC circuit tuned to near fundamental frequency. This reduces the losses at fundamental frequency while retaining the required performance at the series resonant frequency for the whole filter branch.

If higher frequency filtering proved to be necessary, either further tuned arms for 7th and 9th harmonics or preferably a 2nd-order damped filter with minimum impedance at 7th harmonic could be provided, as shown in Figure 18c. The advantage of the multiple-single branch units over the damped filters is the lower effective capacitance at 50 Hz for a given harmonic performance but this is offset by the more precise tuning and stability required for individual components and the larger number of components. The damped filters also have the advantage of effective filtering over a wider frequency range which could be useful in limiting the effect of any parallel resonance between the overhead conductor capacitance and the supply reactance. The different filter characteristics are illustrated in Figure 18d. For detail design of filters for specific applications reference should be made to a suitable textbook such as 'Direct Current Transmission' - Vol. 1 by Kimbark.

### **9.3 Temporary Measures**

The demand information provided by British Rail at the design stage of an electrification project is of a tentative nature in that it is based on assumed timetables. In exceptional cases it is therefore possible after commissioning the supply for the disturbance effects to exceed the design levels.

Excessive system disturbances from either harmonics, voltage dips or negative phase sequence effects could occur for several reasons. These include abnormal running of trains, a heavier loading per train than assumed at the design stage, or the use of a locomotive with a different type of converter. In most of these situations some changes in the railway operating practice and in particular adjustment of the timetable should reduce the disturbance levels.

In addition there are a number of changes which may be made to the supply system to reduce particular types of disturbance. In order to reduce negative phase-sequence effects facilities should be provided at each supply point to allow for changing the phase connections, either by the use of "swinger" connections on post-type insulators or by the provision of connectors on each jumper to facilitate changing the position of the droppers. However it should be appreciated that an improvement in unbalance at one supply point may have repercussions on the negative phase-sequence voltage levels at adjacent points and these should also be checked.

Other methods affecting both unbalance and harmonic levels involve reducing the background level of the disturbance. They include switching the 25 kV system to effect the transfer of a part of a route section from a problem railway supply point to an adjacent supply point, re-arrangement of the supply network to provide an increase in fault level, or re-arrangement of the supply system to change the point of common coupling between the railway load and other consumers.

## **10 EQUIPMENT**

Although much of the equipment associated with providing a.c. supplies for railway traction is the same as for any other load, some plant items differ or have special requirements. Since there is considerable advantage in standardizing the equipment used, the following notes indicate where special features or ratings are required and give guidance where relevant specifications exist.

### **10.1 Transformers**

It is recommended that the CEGB Specification - CEGB RT (1977) be used when seeking tenders.

#### **10.1.1 Ratings**

Existing electrification schemes have used transformers rated (ONAN) at 5, 7.5, 10, 15 and 18 MVA. In the future it is expected that suburban schemes will use 10 MVA units which could be uprated to 14 MVA by the addition of forced cooling equipment. For major supplies the preferred rating will be 18/20.5/26.5 MVA, ONAN/OFAN/OFAF.

### 10.1.2 Tappings

The major supply transformers rated at 18/26.5 MVA should be equipped with off-circuit tap selection on the secondary side giving a tapping range of 0 to +12.5% in 2½% steps. Tap selection should be such as to seek to attain a voltage of 25 kV at the track feeder station under full load conditions. In practice this objective can best be achieved by aiming to give a no-load voltage as close as possible to, but not exceeding, 27.5 kV which is the maximum design value for the railway equipment.

Table 3 shows the optimum transformer tap to be selected for a range of maximum values of 132 kV system voltage up to the upper limit of 145 kV to keep the open circuit secondary voltage between 27 and 27.5 kV.

**TABLE 3 SUPPLY TRANSFORMER TAP POSITIONS**

<b>132 kV System Maximum Voltage (kV)</b>	<b>Optimum Transformer Tap</b>
127-129.1	+ 12½%
130-132	+ 10%
133-135.1	+ 7½%
136-138.3	+ 5%
139-141.7	+ 2½%
143-145	0

Taps are not normally provided on suburban supply transformers rated at 10/14 MVA.

### 10.1.3 Impedance

The nominal impedance will be agreed between British Rail and the Supply Authority and the permitted variation over the tapping range will be stated in the Specification. Unless otherwise agreed, the nominal impedances should be 12% on 18 MVA for the "mainline" transformers and 11% on 10 MVA for the "suburban" transformers.

### 10.1.4 Alternative Supply Voltages

If a 132 kV source of supply is either not available, or is available only at considerable cost brought about, say, by a requirement to construct a lengthy 132 kV line and/or cable, then consideration should be given to the use of transformers connected to either 275 kV or 33 kV sources.

The 275 kV system is associated with the 400 kV system and the voltage generally varies by not more than ±5%. It should therefore be possible to dispense with tappings when using 275 kV connected transformers, and thus eliminate potential weaknesses. It is suggested that a nominal ratio of 275/26 kV could be adopted so as to minimize regulation problems. The establishment of a 275 kV point-of-common-coupling between the railway load and that of

other consumers should ensure that the disturbing effects of the traction load, particularly unbalance, will not be a problem.

Where supplies can conveniently be derived from 33 kV sources using 33/25 kV transformers, the connection of a phase balancer will almost certainly be required.

## **10.2 Underground Cables**

132 kV and higher voltage cable specifications are usually individually prepared and make reference to BEB Specifications, ESI Standards, etc.

For 25 kV cables, EEB Specification No. 305 details a copper conductor polymeric insulated cable with concentric earth return conductor and graphite coated PVC oversheath.

BRB Specification AC5 (1979) covers two-core concentric and single-core cables using copper or aluminium conductors.

### **10.2.1 Application**

As described in Section 11, earth return currents can be excessive if transforming stations and feeder stations are non-adjacent. One way of overcoming this problem is to locate the transformers in compounds adjacent to the feeder stations. This could be achieved by laying 132 kV cabled circuits from the nearest convenient source of supply using either oil-filled or polymeric cables. There is some evidence to suggest that 132 kV single-core polymeric cables may only be marginally more expensive than equivalent 25 kV concentric polymeric cables used to connect non-adjacent transformers and feeder stations.

## **10.3 Overhead Lines**

Two specifications for 25 kV wood-pole overhead lines are available:

SSEB Specification - L21A (1971) is an adaptation of a 33 kV overhead line specification and is a single circuit design using 1 x 400 mm<sup>2</sup> h.d. aluminium conductors (Centipede).

EEB Specification - EEB/25/DC 1980 is for a double circuit design using 2 x 200 mm<sup>2</sup> a.c.s.r conductors (Jaguar).

Other Boards would have to obtain appropriate approvals before constructing overhead lines to these Specifications.

### **10.3.1 Application**

The most economic way of connecting non-adjacent grid or supergrid supply points and feeder stations is likely to be by 25 kV overhead line, but for reasons given in Section 3 this

may be technically undesirable. However, where possible, and where planning permission and wayleaves can be obtained, either single - or double-circuit lines could be constructed.

### 10.3.2 Ratings

The seasonal continuous thermal ratings for 1 x 400 mm<sup>2</sup> Centipede conductor and 2 x 200 mm<sup>2</sup> Jaguar conductor are given in Table 4. These ratings have been derived by CERL from experiments carried out in 1976 and 1977 (reference RD/L/N129/79 - a Statistical Approach to the Thermal Rating of Zebra Conductors Based on Real Weather Observations).

**TABLE 4 OVERHEAD LINE CONDUCTOR RATINGS  
Amperes Per Conductor (Operating at 75°C)**

Cable Type	Winter	Normal	Summer
Centipede	960	920	850
Jaguar	610	590	540

It is possible that higher ratings could be allocated, depending on the circuit loading cycle or on the ground clearances available. The Overhead Line Engineers for the CEGB or SSEB will give advice on ratings for particular locations.

## 10.4 25 kV Switchgear

This is covered by the BRB Specification AC10/3 - General Specification for 25 kV Single-Phase 50 Hz Switchgear.

### 10.4.1 Equipment at the Feeder Station

The use of enclosed, metalclad, 25 kV switchgear incorporating vacuum circuit-breakers is recommended for standardisation with British Rail switchgear. British Rail will order and their contractors will install the complete switchboards, but ownership of the equipment on the incoming circuit, up to and including the circuit breakers, will pass to the supply authority. Separate outdoor disconnectors and earthing switches, owned, maintained and operated by the Supply Authority, should also be provided if the transforming and feeder stations are not adjacent.

Facilities additional to those associated with the British Rail remote supervisory control and indication system, should be provided at those locations where there is no 25 kV circuit breaker at the transforming station, to enable the position of the incoming feeder circuit breakers and the operation of the associated trip circuit supervision relays to be indicated in the Supply Authority Control Centre.

A telephone extension from the supply authority PBX system should be provided in the feeder station. (See sub-paragraph 11.4.5.5.)

### **10.4.2 Equipment at the Transforming Station**

The equipment to be provided will, in part, be dependent on the distance between the transforming and feeder stations, but in general will comprise outdoor isolating and earthing facilities which should be of the double-pole, ganged type. If a circuit breaker is required for any reason, this should again be of the vacuum interrupter type with connections adapted for Supply Authority use. Alternatively, suitable designs of oil or SF<sub>6</sub> switchgear could be used.

A relay supplied from the 110 V winding of the metering voltage transformer should be provided to enable an indication of the availability of the 25 kV supply to be given in the British Rail Electrical Control Room.

### **10.4.3 Arrangement of Switchgear and Associated Equipment**

This is covered in Sections 3, 11 and 12, but it should also be noted that, at the feeder station end, special precautions will be required to guard against accidental contact with live equipment.

These could include the use of anti-climbing features and cheval-de-frise to protect the feeder stations, screening to protect the connections from the Supply Authority equipment to the feeder stations, and fencing to protect the Supply Authority sealing end and isolating/earthing compounds. The precautions shown in Figure 19 are deemed to be sufficient to comply with the Electricity Supply Regulations 1937 and the Electricity (Overhead Lines) Regulations, 1970.

## **10.5 Metering**

In England and Wales, CEGB are responsible for the application of tariff metering and a modification of their bulk supply tariff is used. In Scotland, SSEB have employed a tariff structure which differs considerably from that used by CEGB in that it is kVA based as opposed to kW based. The instrumentation used is therefore different and it is not possible to compile a common section on metering equipment. However, guidance can be obtained by reference to the documentation listed below.

Engineering Recommendation M.24 - Code of Practice for the Metering of Supplies from the CEGB.

TPS6/19 - Application of Metering to Tariff Circuits.

### **10.5.1 Types of Equipment**

Existing tariff metering schemes have used electronic summation equipment, but it is expected that most future schemes will employ a microprocessor. It should be noted that for British Rail supplies, a voltage transformer ratio of 26,400/110 V is adopted as standard to suit the meter gear ratio.

## **10.6 Communications**

Direct telephone links should be provided between Supply Authority Control Centres and British Rail Electrical Control Rooms. Where such links cannot be provided, special arrangements such as the use of high priority ex-directory British Telecom telephone numbers may be utilised to ensure a rapid and reliable means of communication.

## **10.7 Supply Booster Transformers - Three/Two-phase Transformers - Phase Balancers**

No suitable specification exists for supply booster transformers. Detailed design would depend on individual site parameters such as potential loading conditions and loop impedances. Similarly, phase balancers and filters would require individual design and specification.

### **10.7.1 Application**

The connection of booster transformers at transforming stations, for the purpose of encouraging return current to flow via the neutral conductor as opposed to via earth, is shown in Sections 3 and 12, and the effectiveness of a booster is demonstrated in Section 3.

The use of neutral booster transformers will increase the cost of connection of supply, could have a small detrimental effect on reliability of supply, and will marginally increase voltage regulation. Nevertheless, the use of neutral boosters will virtually eliminate the passage of return current via earth.

The use of three/two-phase transformers (e.g. Scott connected) could, if the two single-phase secondary windings were equally loaded, present a balanced three-phase current on the primary side. However, in practice the two secondaries will seldom be equally loaded as the transformer must feed two isolated sections of track. In addition, account must be taken of the possibility of an outage of at least one transformer in the supply system which could result in additional loading on one secondary winding at each adjacent track feeder station. Unbalance conditions would then prevail and the use of three/two-phase transformers cannot therefore be recommended.

The use of phase balancers to limit disturbances caused by unbalance is described in Section 9. Associated filtering equipment would be required to deal with harmonics produced by the balancer and other sources.

## 11 EARTHING

The earthing system for a railway supply can involve separate sites for the transforming and feeder stations. It will also include a distributed earth associated with the railway supply return conductor.

### 11.1 Earthing Arrangements on British Rail's Track System

Both running rails of British Rail's track are, in effect, lightly insulated from earth. Normally one rail is used for signalling purposes; the other, the traction return rail, is used as a conductor for traction current. The traction return rail is bonded to the overhead line supporting structures at the side of the track, thereby forming a multiple earthed system through the footing resistances of the supports. At intervals, inter-track bonds join the traction return rails of adjacent tracks. At feeder stations, bonds are made between the traction return rails and the return current busbar which is otherwise unearthed except for a connection to the nearest adjacent overhead line support structure. All bonds are made of flexible cables but, due to the passage of trains and the resulting movement of the rails, or due to track maintenance work, it is not unknown for the continuity of bonds to become interrupted. However it is extremely unlikely that the return current busbar will become completely disconnected from earth.

### 11.2 Earthing of the Supply Authority's 25 kV System

There are two main alternatives to the method of earthing to be adopted for the 25 kV system and the advantages and disadvantages of these are summarised in (a) and (b) below.

#### (a) 25 kV Winding Earthed at the Transformer

##### Advantages

1. Safety to Supply Authority personnel and plant is enhanced by the fact that the 25 kV system is earthed by a connection where no physical movement takes place.
2. Avoids any possible danger by the failure to close the earth disconnector before switching takes place.

##### Disadvantages

1. The grid transformer earth, forms an alternative path for the traction return current via earth which would otherwise flow only along the supply return conductor. Earth currents are undesirable since they could cause interference to communication circuits and perhaps corrosion troubles to water, gas and other underground services. The magnitude of the earth return current depends upon several factors:

- (i) the distance between the 132/25 kV transforming substation and British Rail's feeder station - greater separation generally increases the earth current. See paragraph 3.2;
- (ii) the type of 25 kV circuit - if wholly or partly by overhead line the earth return current will be greater than if concentric cable formed the entire circuit. See sub-paragraph 3.2.4;
- (iii) the geographic route and topography of the railway track in the neighbourhood of the transforming and feeder stations. See paragraph 13.2.

(b) **25 kV Winding Earthed by the Traction Return Rail**

**Advantage**

The flow of earth return current between the railway feeder station and the 132/25 kV transformer site is not possible.

**Disadvantages**

1. Earthing of the 25 kV system, particularly that part for which the Supply Authorities are operationally responsible, is not as secure as with directly earthed grid transformer.
2. In the event of a break in the supply return conductor there is a possibility of:
  - (i) damage to plant due to high potentials caused by lightning and charged clouds;
  - (ii) overstressing of 25 kV cable insulation by a rise in potential between the outer conductor and earth. By fitting neutral voltage displacement protection, insulation breakdown due to electrical overstressing can be avoided.

The vulnerability of the track bonds and the Supply Authority's responsibilities under the Factories Act 1961, Electricity Supply Regulations 1937 and the Health and Safety at Work Act 1974 for safety to personnel and plant should be borne in mind. It is recommended that the supply return conductor side of the 25 kV winding of the 132/25 kV grid transformer be connected to the 132/25 kV substation earth by a bolted link. However, Figure 4c shows an arrangement where the grid transformer is normally unearthed.

## **11.3 Design of Earthing Systems**

### **11.3.1 General**

The design of the earthing systems for the 25 kV primary system and also for the non-current carrying metalwork of plant and equipment must be such as to prevent:

- (a) danger to personnel and plant due to the possibility of transferred potentials between British Rail feeder stations and Supply Authority compounds and substations at times of fault on the 25 kV contact wire and catenary system;
- (b) the possibility of work being undertaken on equipment passing load current;
- (c) the overheating of equipment by the passage of current along undesirable paths.

### 11.3.2 Design Criteria

In designing an earth system, note should be taken of:

- (a) The advice given in British Standard Code of Practice CP1013:1965 which recommends that an earth connection shall not only be of low resistance but also of low reactance, i.e. as short and as free from changes in direction as practicable.
- (b) Engineering Recommendation S5/1 - "Earthing Installations in Substations".
- (c) The directive issued by the International Telegraph and Telephone Consultative Committee which gives limits for the maximum rise of earth potential at a substation where British Telecommunications equipment is to be installed without special protection for their equipment or personnel. These limits are 430 V on systems protected by overcurrent protection and 650 V where high speed protection is provided and which are designated as 'high reliability systems'. These limits are now also used throughout the Electricity Supply Industry as a criterion for safety due to a rise in earth potential.
- (d) Whilst not directly concerned with the design of a British Rail supply point, it may well be that 415 V supplies are already given to British Rail for lighting and heating at a railway station and for heating track points in the same vicinity as the proposed new supply point. Should this be the case, attention is drawn to paragraph 19.3 of Engineering Recommendation G.12/2 mentioning that special care is needed in designing the bonding of metalwork to the Electricity Board's earthing terminals at premises adjacent to a.c. electrified railway lines. It is also pointed out that consideration should be given to the possible effects of system faults where the traction supply transformer is located more than 100 m from the track and independently earthed.

### 11.4 Earthing of Non-Current Carrying Metalwork

Sub-paragraphs 11.4.1 to 11.4.5 deal with the earthing arrangements and safety precautions needed for the several plant items at different site locations depicted schematically in Figure 4b.

#### **11.4.1 Disconnecter and Earthing Switch at the Transforming Station**

The non-current carrying metalwork of the disconnector and earthing switch should, together with the earthing switch terminal, be connected to the 132/25 kV substation earth.

#### **11.4.2 25 kV Cable Sheaths**

If the 25 kV cables terminate in the 132/25 kV transforming station and have metallic sheaths, the sheaths should be earthed through links to the 132/25 kV substation earth.

Should the cables terminate in a compound external to the 132/25 kV substation, the earthing of the sheaths should be achieved by earth spikes driven into the ground specifically for that purpose. If required, these earth spikes may also be used to earth other non-current carrying metalwork within the same compound. (Ref. sub-paragraph 11.4.3).

#### **11.4.3 Isolating Compound Adjacent to British Rail's Feeder Station**

The non-current carrying metalwork of the disconnector and earthing switches, as well as the earthing terminals of the earthing switches, should be connected to an earth spike(s) set midway between the disconnector and cable sealing end or overhead line terminating structure. In the event of a metallic sheathed cable being provided, the sheath should be connected through a link to the same earth spike(s). (Ref. sub-paragraph 11.4.2). No bonding should be made between the compound earthing system and British Rail's return current busbar.

The above measures ensure that:

- (a) Earthing of the 25 kV cable for maintenance purposes can be achieved independently of the 25 kV feeder station thereby avoiding danger due to transferred potentials. They also avoid the formation of a parallel path between the feeder and transforming stations for the passage of traction return current from any other transformer still in commission.
- (b) The passage of traction return current along the 25 kV cable sheath is kept to a minimum.

The compound fence should be independently earthed and should not be connected to the 25 kV cable sheath/disconnector/earthing switch earth, or to the non-current carrying metalwork of British Rail's 25 kV feeder station.

A touch distance separation of two metres must be maintained between any exposed item of metalwork not bonded to the same earth system. For example, the compound fence must be set back two metres from the metalwork of the cable sealing-end structure, disconnector 1L3 and earthing switches 1L1A and 1L1B. The compound fence must also be two metres away from the adjacent side or end of British Rail's 25 kV switchgear enclosure. If there is an outside opening door which would effectively reduce the touch distance between the

enclosure and the compound fence, the distance should be increased to provide two metres clearance to the open door.

To obviate danger to personnel, any 25 kV connections crossing the passageway between the compound fence and the enclosure at a height less than six metres should be provided with an overhead insulating barrier extending for a distance of one metre on each side of the connection and so constructed that a ball can roll off (see Figure 19).

This requires a dispensation from the provisions of the Electricity (Overhead Lines) Regulations 1970 and a request for this should be made by the Area Board concerned to the Secretary of State for Energy (Chief Engineering Inspector), Electricity Division, Department of Energy, Thames House South, Millbank. For supply points in Scotland, application should be made to the Secretary of State for Scotland, Energy Division, New St. Andrew's House, St. James Centre, Edinburgh.

#### **11.4.4 Structure Mounted Cable Sealing-End, Disconnecter and Earthing Switches Adjacent to British Rail's Feeder Station**

Where there is no separate ground-level isolating compound, the 25 kV sealing-end, disconnecter and earthing switches may be high-level structure mounted (see Figure 19). The structure must be so sited that any of the non-current carrying metalwork associated with the structure including the raised operating handle and the earth mat for safeguarding operational personnel should be two metres plus the width of any access door away from the nearest British Rail metalwork. The earth spike or spikes for the metalwork of the disconnecter and earth switches, should be independent of and at least three metres from any British Rail earth.

The above measures ensure that earthing of the cable can be achieved independently of the 25 kV feeder station, thereby avoiding danger due to transferred potentials and without forming a direct metallic parallel path between the feeder and transforming stations for the passage of traction return current.

#### **11.4.5 Safety Precautions on Associated Equipment**

Precautions needed on associated equipment (protection, control, indication and telecommunications), for safety reasons, are listed below.

- (a) No electrical bond, other than that formed by the supply return current conductor, shall be established between a British Rail return current busbar and an Electricity Board substation or compound earthing system. For instance the armouring and/or metallic sheath of any interconnecting multicore cable must be 'gapped' or otherwise insulated and protected from British Rail metalwork at the feeder station.
- (b) An Electricity Board multicore cable which terminates at one end within British Rails' 25 kV switchgear enclosure should be equipped with 5 kV insulated terminal blocks and 5 kV insulated isolation plugs at both ends of the cable.

- (c) The secondary wiring of Electricity Board control, protection and indication circuits within British Rail's 25 kV switchgear enclosure should be sleeved for additional electrical insulation.
- (d) The connections between the feeder station and any magnetic-bolt interlock applied to a disconnector associated with an incoming vacuum circuit breaker should be via a 1:1 isolation transformer.
- (e) An isolation transformer should be provided for the Electricity Board telephone in British Rail's feeder station annex.
- (f) Telephones should not be provided in any 25 kV cable sealing-end/isolating compound.

## **12 PROTECTION**

Figures 20a to 20f set out recommended schemes of protection for various supply configurations. Since the protection arrangements differ between these options, the application philosophy for each has been summarised in the following.

### **12.1 H.V. Protection**

The h.v. protection provision is common to all six of the arrangements considered and should comprise:

- (a) a circulating current protection driven from parallel connected c.t's in the h.v. bushings;
- (b) a two-pole overcurrent protection driven from two h.v. bushing c.t's;
- (c) transformer buchholz and winding temperature protection. (The w.t. settings should be: alarm 100°C; trip 120°C).
- (d) a 'qualitrol' pressure relief device, arranged to alarm or trip.

The h.v. bushings should also accommodate c.t's forming part of the h.v. connections or h.v. feeder protection, the duty depending on the type of h.v. supply. Where the supply transformers are supergrid transformers the h.v. protection arrangements would need to comply with supergrid protection policy to ensure required protection reliability, e.g. through the use of duplicate relays.

## 12.2 25 kV Protection

### 12.2.1 Supply Arrangement A (Figure 20a)

Here the transforming and feeder stations are adjacent and the transformer neutral end is solidly earthed at the transformer. Switching is by a single-pole 25 kV circuit breaker at the feeder station.

The l.v. winding and 25 kV phase conductor should be protected by a high impedance circulating current protection while the neutral is unprotected. To detect a broken neutral conductor condition, a suitably set IDMT directional earth current protection relay (equipped with a plug bridge for monitoring purposes) should be provided, driven from a c.t. in the transformer neutral earth connection. The directional feature is necessary to cater for the two transformer arrangement (existing or future) where return current from the faulted circuit may use the healthy circuit neutral and transformer earth connection. The healthy circuit directional earth current protection would be polarised to be unresponsive to this current. Conventional IDMT overcurrent protection should be provided at the 25 kV circuit breaker.

### 12.2.2 Supply Arrangement B (Figure 20b)

Here the transforming and feeder stations are distant from each other and the transformer neutral end is not earthed at the transformer. Switching is by a single-pole 25 kV circuit breaker at the feeder station.

The transformer l.v. winding should be separately covered by a circulating current protection while the 25 kV phase conductor should be covered by a pilot wire protection. Conventional IDMT overcurrent protection should be provided at the 25 kV circuit breaker and there should be surge-proof intertripping from the transforming station to the feeder station. As an alternative to the use of surge-proof intertripping, the phase conductor pilot wire protection may be of a type with an optional intertripping feature such as "Translay S".

The neutral conductor should be covered by a pilot wire protection and neutral voltage displacement protection. These are necessary to cater for two types of fault. A broken neutral conductor clear of earth, results in a rise of potential on the transformer side of the break which if sustained would be detrimental to cable insulation. Neutral voltage displacement protection detects and clears this fault. A broken neutral conductor to earth on the transformer side however would not be detected by neutral voltage displacement protection but would be a hazard since load current from the faulted neutral would return via pilot cable sheaths, third party property, etc. To detect and clear this fault a neutral pilot wire protection should be provided as shown.

While there is a third fault condition (broken conductor to earth on the British Rail feeder station side) this is electrically no different from the broken conductor clear of earth case since, with interruption of load, the earthed conductor carries no current.

### 12.2.3 Supply Arrangement C (Figure 20c)

Here the transforming and feeder stations are distant from each other and the transformer neutral end is earthed at the transformer. Switching is by a single-pole 25 kV circuit breaker at the feeder station.

The transformer l.v. winding should be separately covered by a circulating current protection while the 25 kV feeder phase conductor should be covered by a pilot wire protection. Conventional IDMT overcurrent protection should be provided at the 25 kV circuit breaker and there should be surge-proof intertripping from the transforming station to the feeder station. As an alternative to the use of surge-proof intertripping, the phase conductor pilot wire protection may be of a type with an optional intertripping feature such as "Translay S".

Because the transformer neutral is solidly earthed at the transformer there can be no rise of neutral potential as a result of a broken neutral conductor. In the case of a broken neutral conductor clear of earth, the return current from the faulted circuit uses an earth path (and the neutral of parallel circuit if such exists) and a directional earth current protection relay should be provided, driven from a c.t. in the transformer neutral earth connection, to trip the circuit for this unhealthy condition.

In the case of a broken neutral conductor to earth on the transformer side, the return current from the faulted circuit has several paths, namely:

- (a) From the track earths to the faulted neutral and thence by neutral conductor to transformer neutral,
- (b) From track earths via earth path and transformer neutral earth connection to transformer neutral,
- (c) From feeder station return current busbar to the faulted circuit transformer neutral via the parallel circuit neutral and earthing system of any other available healthy transformer circuit.

Depending upon the position of the fault and upon the resistance of the fault earth, the proportion of load current in the faulted circuit neutral earth connection may be insufficient to operate the directional earth current protection. To cater for this condition the neutral conductor should be covered by a pilot wire protection.

Where the broken neutral is to earth on the feeder station side, all the faulted circuit current returns via the transformer neutral earth connection and the circuit is tripped by directional earth current protection.

### 12.2.4 Supply Arrangement D (Figure 20d)

Supply arrangement D is the same as C above except that a booster transformer is provided at the transforming station end, connected in the transformer neutral. The mode of connection is such that it inserts a high impedance in the earth path while providing a low impedance neutral return. This arrangement ensures that only a small fraction of the total load current

takes the earth path during normal running. Protection arrangements should be the same as in case C but the directional earth current relay is given a lower setting.

### **12.2.5 Supply Arrangements E and F (Figures 20e and 20f)**

Supply arrangements E and F shown in Figures 20e and 20f are similar to B and C respectively, except that a local 25 kV circuit breaker is provided at the transforming station end in addition to the 25 kV circuit breaker at the feeder station. Intertripping between the stations thus becomes unnecessary, but apart from tripping details, the protection provision remains the same.

### **12.2.6 Possible Parallel Operation of Supply Transformers**

Sub-paragraph 2.1.1 describes conditions where supply transformers may be operated in parallel. The implications of parallel operation for the protection system are as follows.

Unit type protections, by definition, perform their correct function irrespective of whether the transformer operates as a single unit with no back-feed or as one of a pair bussed on the 25 kV side.

The directional feature of the earth current protection relay (Figures 20a, c, d and f) covers the particular case of paralleled transformers with a broken neutral on one circuit (Figure 20g). Assuming all the load current returns via the healthy neutral (in fact a proportion takes the earth path) this divides at the transforming station, half passing into the healthy circuit winding directly and half passing into the faulted circuit winding via the neutral/earth connections of each transformer. Since both neutrals and their current transformers carry the same current, the associated earth current relays must be voltage polarised such that the healthy circuit relay stabilises and the faulted circuit relay operates.

Neutral voltage displacement protection is relevant only to the single transformer broken neutral case. Where two transformers are paralleled the neutral point of the unit associated with the faulted circuit is held at zero potential, ignoring impedance drop due to load, (Figure 20h) and no overstressing of neutral cable insulation occurs.

## **12.3 British Rail Protection Policy**

The primary protection scheme on the incoming 25 kV feeder circuit breakers is co-ordinated with and forms an integral part of the protection system provided at the transformer, see Figures 20a to 20f. In addition an inverse definite minimum time over-current relay is provided to cover 25 kV busbar faults or sustained over-current, and to afford back-up protection to the outgoing track feeder circuit breakers.

The protective system provided for the track feeder circuit breakers is a single-phase version of the standard high-voltage transmission distance-measuring relay scheme. This employs a three-zone scheme of distance protection having a mho characteristic, with zone 1 providing protection for 80 to 85% of the protected section and zones 2 and 3 providing time-delayed

protection for faults not covered by zone 1 as well as back-up protection for faults in adjacent sections. Zone 1 fault clearance time is about 90 ms.

Protection against high impedance faults or sustained overloads on track feeder circuit breakers is provided by thermal over-current relays.

All bus section circuit breakers are equipped with instantaneous overcurrent protection. This is operative only whilst the breaker is being closed in order to prevent mal-discrimination with the protection on the track feeder circuit breakers. Bus section circuit breakers at mid-point track sectioning cabins are also provided with voltage sensing relays which allow closure only when one of the busbar sections is not energised.

### **13 SYSTEM MONITORING**

Since railway supply points will not normally be manned, there is little merit in building in a large amount of instrumentation as a permanent facility. It is more important that adequate facilities exist for connection of suitable monitoring equipment, either during commissioning or when any special investigation is required. For this purpose it is desirable that the necessary c.t. and v.t. connections be brought out to a test block to which connection can be made without interference to any other plant. The following signals should be made available.

- (1) 25 kV voltage from secondary v.t. on each traction supply transformer.\*
- (2) Current in secondary circuit of each transformer.\*
- (3) Current from bar type c.t. on each transformer earth connection or provision to be made for space to fit a clip-on c.t.

\* Similar signals will also be available at the feeder station.

It is anticipated that the facilities will be used for the following:

#### **13.1 Harmonic Distortion**

If harmonic complaints are received, these are most likely to be due to problems on the lower voltage distribution network and the question to be resolved will be the contribution of the railway distortion to the level at say the local 33 kV busbar. Facilities should be available for harmonic voltage or current measurements at 33 kV substations and these could be correlated with simultaneous measurements of harmonic current at the railway supply point. Measurement of harmonic current from each 25 kV secondary can be used to provide data for calculation of harmonic penetration. Measurement of the harmonic voltage at 25 kV is possible though probably of rather less value. Provision of an accessible signal from the 132 kV primary capacitor bushings would enable a more direct measure of the harmonic voltage on the supply system for comparison with limits.

## 13.2 Earth Currents

The separate earths of the supply transformer and of the track are likely to give rise to some earth return current and facilities should be available for checking this when the supply is commissioned. The problem is most likely to occur where the transformer is remote from the railway but problems can occur with trackside transformers where the track supplied is on a curve so that the earth return path across country is electrically shorter than the circuit via the return conductor. A recording ammeter connected to a c.t. on the transformer earth connection will establish whether remedial measures have to be adopted.

## 13.3 Plant and System Loading

Where problems associated with plant loading occur, recording ammeters can be installed to monitor 25 kV feeder current. Recording ammeters would also be useful for investigating system unbalance leading to excessive negative phase sequence voltages. As with harmonics, the problem of excessive n.p.s voltage levels will be manifested at consumers' plant and the measurement of level is best made at a 33 kV supply point where three-phase voltage signals are available for operation of n.p.s recording equipment. Time correlation between records of n.p.s voltage level at the 33 kV bar and the railway loading will indicate the extent to which the railway supply contributes to the problem. It should be appreciated that depending on the phase relationship of the railway supply and other unbalanced loads from industrial or domestic sources the railway supply may reduce or increase the n.p.s. level. It is essential before any remedial action be attempted that the relationship between the unbalanced components due to the railway and other loads be correctly assessed.

## 14 OPERATIONAL SAFETY ASPECTS

Operational Procedures associated with electricity supplies from grid supply points to railway feeder stations for traction purposes are formulated and agreed by British Rail and the Electricity Boards and are included in Engineering Recommendation G.38. Details of the supply points covered by the Procedures are normally catered for by the inclusion of appendices to the Operational Procedures.

In drawing up appendices for new supply points, it may be necessary to include Operational Limitations to avoid:

- (a) Working on equipment passing traction return current and
- (b) Danger due to transferred potentials.

To elaborate on the general statement made above, paragraphs 14.1 to 14.7 below deal with work on particular items of 25 kV plant and highlight the unusual technical and operational aspects which arise on a 25 kV single-phase traction supply system. These aspects need to be considered before work is undertaken. Whilst work on a particular item of plant is being carried out work on other items may not be possible. These limitations, together with the reasons for them, are stated.

The paragraphs do not detail comprehensively the switching, isolation and earthing procedures necessary for the issue, say, of a Permit-to-Work. No mention is made of action on the 132 kV section of the 132/25 kV transformer circuit or on the British Rail 25 kV system, since work on such circuits, both 132 kV and 25 kV is already governed by Electricity Board and British Rail Safety Rules.

Reference should be made to Figure 21 for switchgear numbering.

#### **14.1 General**

On 25 kV a.c. single-phase systems a supply return conductor must be treated with caution since,

- (a) A current may still be flowing in the conductor even though its associated live conductor is out of commission;
- (b) It is ultimately connected to British Rail's return current busbar which may rise in potential when faults occur on the track system.

#### **14.2 Work on Equipment on the Transformer Side of Transformer Disconnecter 1T3**

1T3 would be opened, earth switch 1L1 left open and temporary earths affixed on the transformer side of 1T3.

#### **14.3 Work on Transformer Disconnecter 1T3 and Associated Earth Switch 1L1**

1T3 and 1L3 would be opened, 1L1 and 1L1A closed and temporary earths affixed on the transformer side of 1T3 and on the line side of 1L1. 1L1B would remain open since its closure could form a parallel path for the passage of traction return current from the transformer remaining in service via 1L1A and 1L1 which is the equipment being worked upon. Under these conditions, work would also be possible on the transformer side of 1T3.

#### **14.4 Work on the 25 kV Circuit (Underground Cable or Overhead Line) Between 1T3/1L1 and 1L3/1L1A**

1T3 and 1L3 would be opened, 1L1 and 1L1A closed. 1L1B would remain open.

Under these conditions, no work would be permitted on 1L3 or on the feeder station side of 1L3, since this would require the closure of 1L1B which would form a parallel path for the passage of traction return current from the transformer remaining in service, via 1L1A, the circuit to be worked upon and 1L1.

#### **14.5 Work on Line Disconnectors 1L3 and Associated Earth Switches 1L1A and 1L1B**

1L3, 1T3 and F1/1 would be opened. 1L1 would remain open. 1L1A and 1L1B would be closed and temporary earths affixed on the line side of 1L1A and on the feeder station side of 1L1B. Care should be taken to ensure that the temporary earths are returned to the local earth point E2 and not to the feeder station earth E1. Under these conditions, no work would be permitted on any part of the 25 kV circuit between 1L3 and 1T3 for the following reasons:

- (a) Should a fault occur on British Rail's 25 kV traction system, the return current busbar would rise in potential. The closed earth switches 1L1A and 1L1B or portable earths would effectively transfer some of this potential to the supply return conductor between 1L3 and 1T3.
- (b) If work were to be undertaken on the transformer side of 1L3, 1L1 would have to be closed or temporary earths applied in the transforming substation. These, together with the closed earth switches 1L1A and 1L1B would form a path for the passage of traction return current. In any event, should the 25 kV circuit be formed wholly by a metallic sheathed underground cable, a parallel path for the passage of traction return current is inevitably formed by the sheath and the closed earth switches 1L1A and 1L1B.

#### **14.6 Work on F1/1 and/or Removal of the 25 kV Connection Between 1L3 and Circuit Disconnector F1/1**

F1/1 and 1L3 would be opened. After isolating the whole of the section of the 25 kV switchboard concerned at the bus-section switch and at all outgoing circuits, the busbar would be earthed by the bus-section breaker and temporary earths applied to all circuit breaker roof bushings including that of the incoming feeder circuit. 1L1B would be closed and a temporary earth applied to the spigot on the 1L3 side of F1/1.

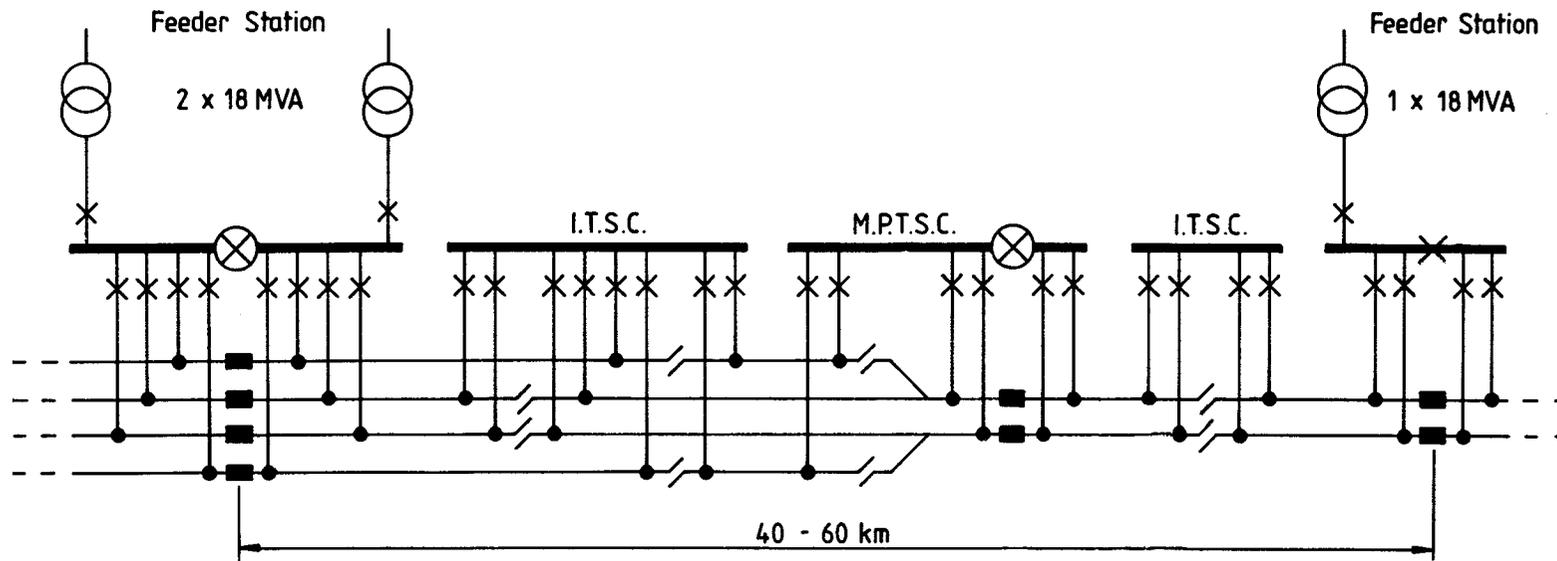
Whilst this situation exists, work would be prohibited on:

- (a) The supply return conductor between 1L3 and the return current busbar since this connection is needed to ensure that there is no appreciable voltage difference across F1/1 and/or the 25 kV connection between F1/1 and 1L3.
- (b) 1L3, 1L1A and 1L1B and any part of the 25 kV circuit between 1L3 and 1T3, for a reason similar to that given in paragraph 14.5(b).

#### **14.7 Work on or Removal of the Supply Return Conductor Between M3 and the Return Current Busbar**

2L1B would be closed. It would also be necessary to isolate British Rail overhead line equipment in the area of the feeder station.

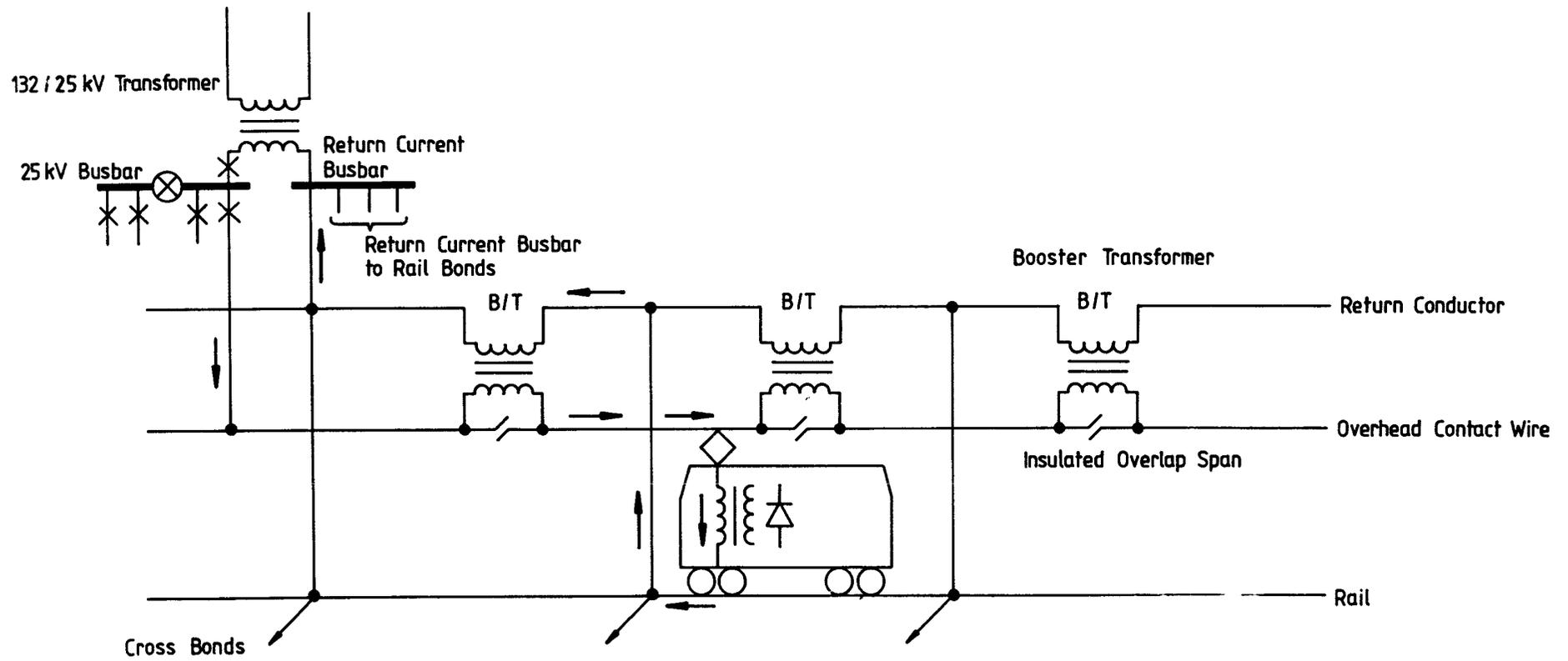
These precautions are necessary to avoid danger, due to a possible rise in potential, between the two ends of the supply return conductor at the moment disconnections are being made.



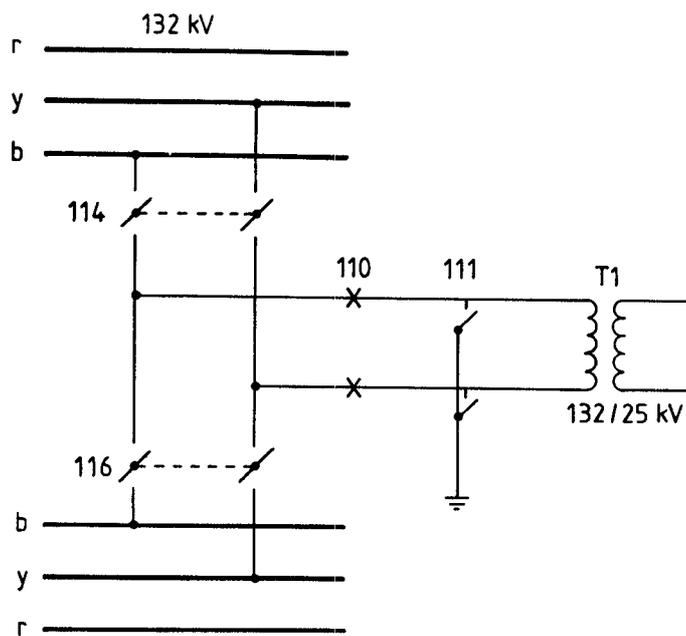
**KEY**

- X— Circuit breaker, normally closed.
- ⊗— Circuit breaker, normally open
- Neutral section insulator assembly
- /— Overlap
- ( )— 132 / 25kV transformer
- I.T.S.C. Intermediate track section cabin
- M.P.T.S.C. Mid-point track section cabin

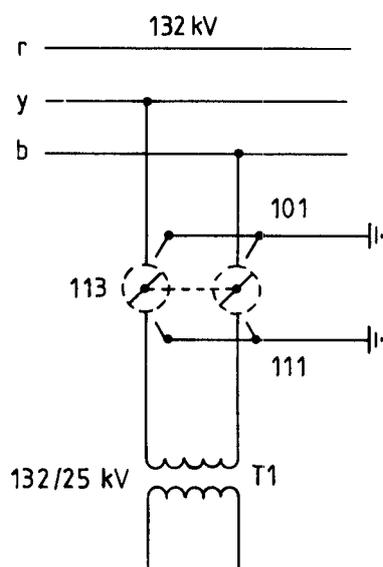
**FIGURE 1: DIAGRAM OF TYPICAL 25 kV MAJOR FEEDING ARRANGEMENT**



**FIGURE 2: DIAGRAM OF BOOSTER TRANSFORMER SYSTEM**

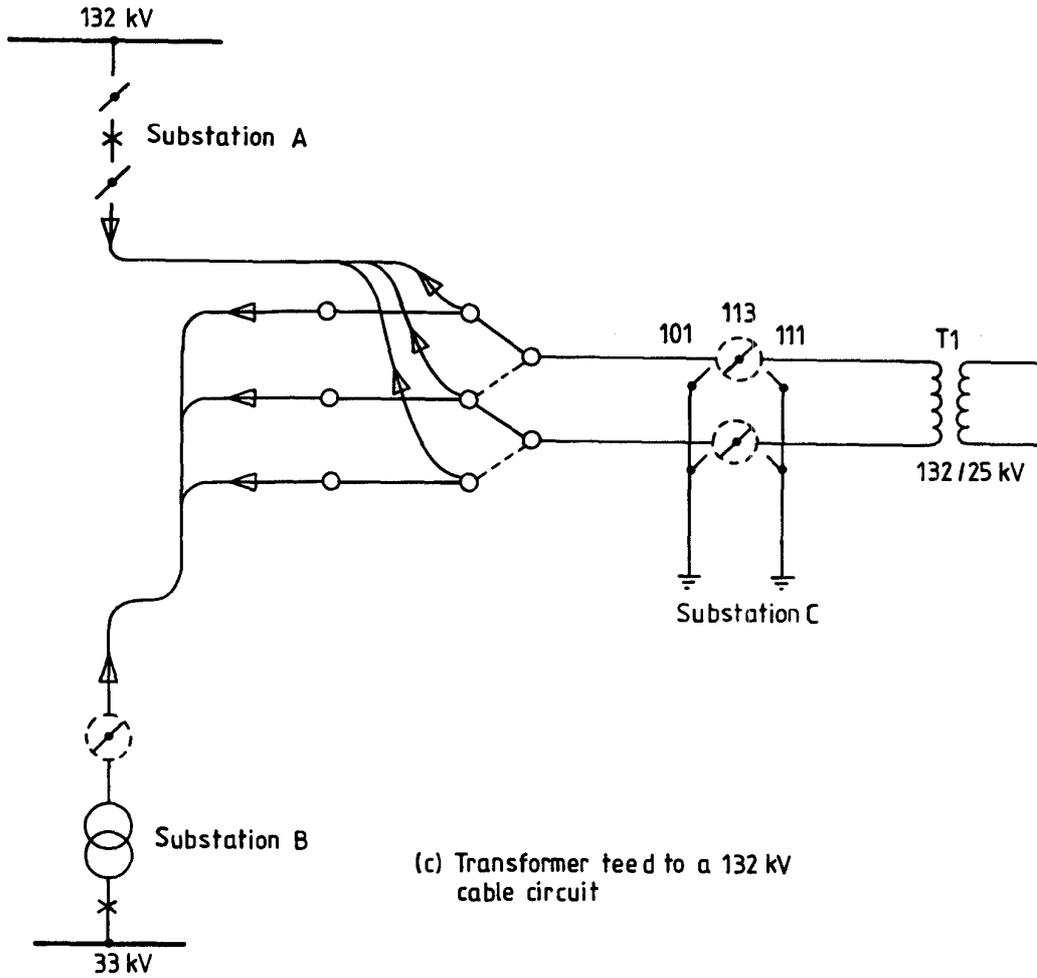


(a) Transformer switched on a 132 kV busbar

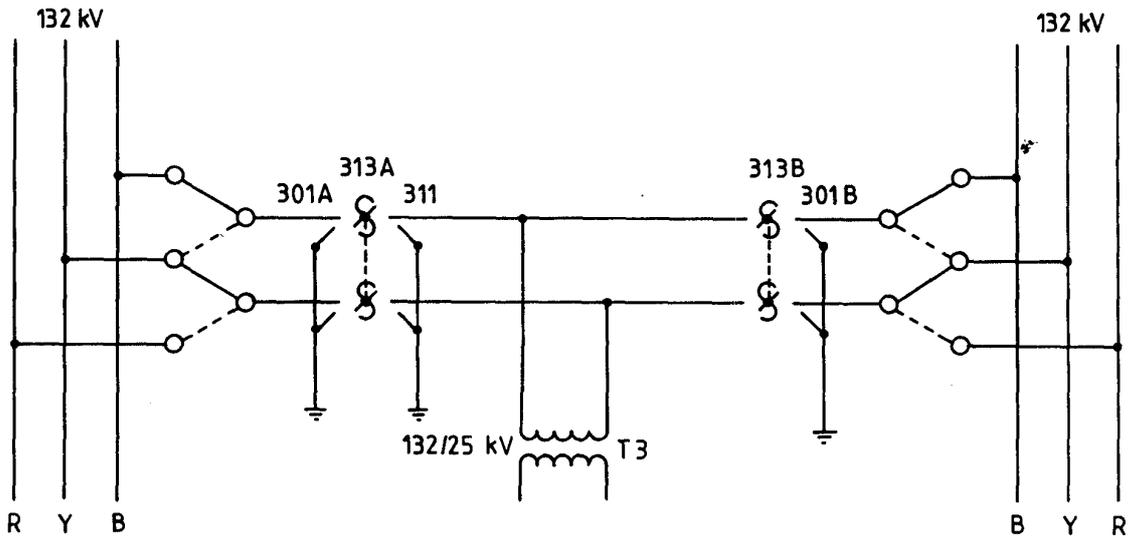


(b) Transformer fed to a 132 kV overhead circuit

**FIGURE 3(a) AND (b) SELECTION OF 132 kV PRIMARY CONNECTIONS**



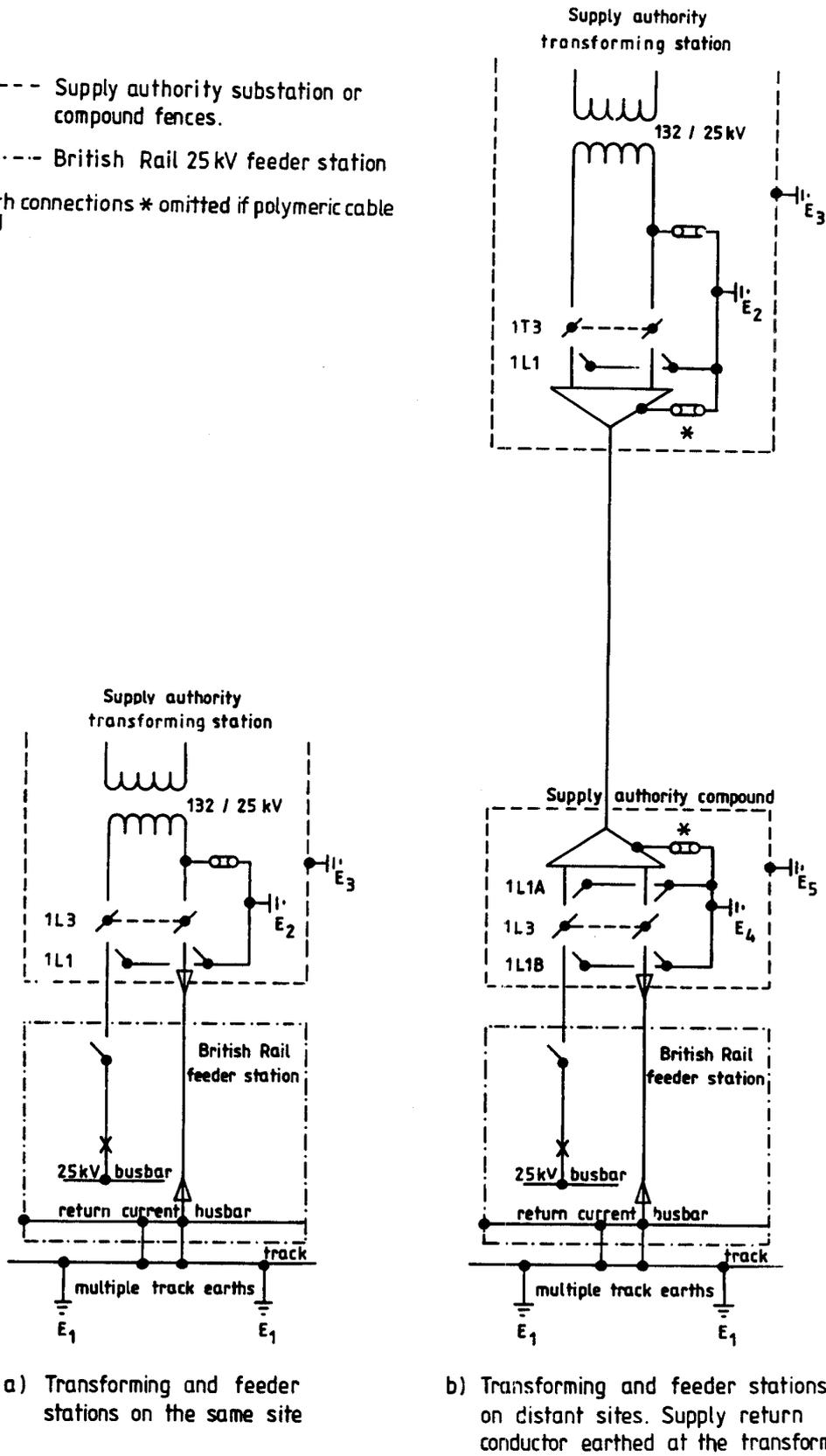
(c) Transformer feed to a 132 kV cable circuit



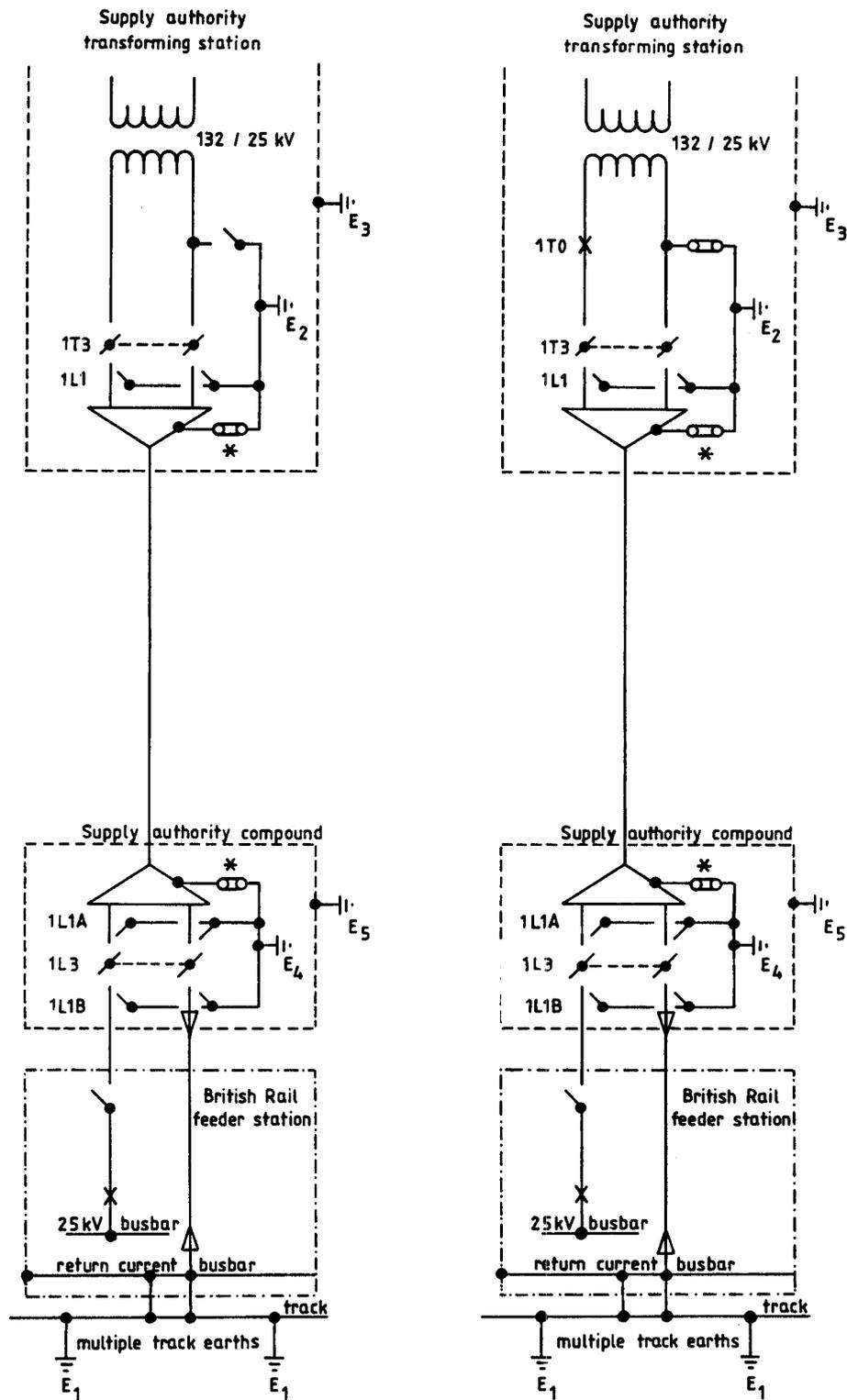
(d) Transformer selectable to two 132 kV overhead circuits

FIGURE 3(c) AND (d): SELECTION OF 132 kV PRIMARY CONNECTIONS

----- Supply authority substation or compound fences.  
 - - - - - British Rail 25 kV feeder station  
 Earth connections \* omitted if polymeric cable used



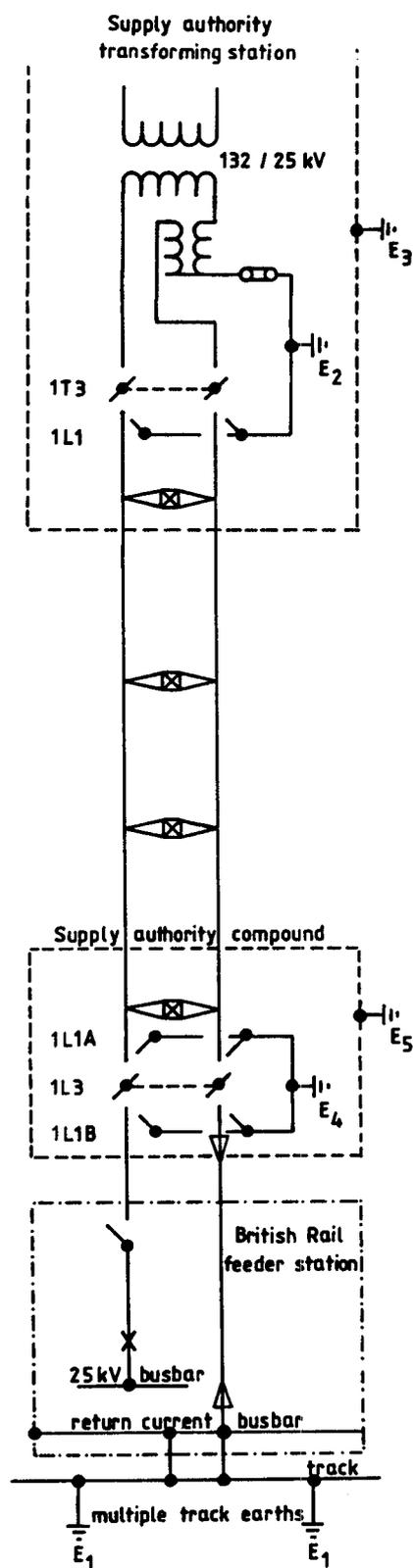
**FIGURE 4(a) AND (b): CONNECTIONS FOR VARIOUS TYPES OF SUPPLY POINT**



c) Transforming and feeder stations on distant sites. Supply return conductor unearthed.

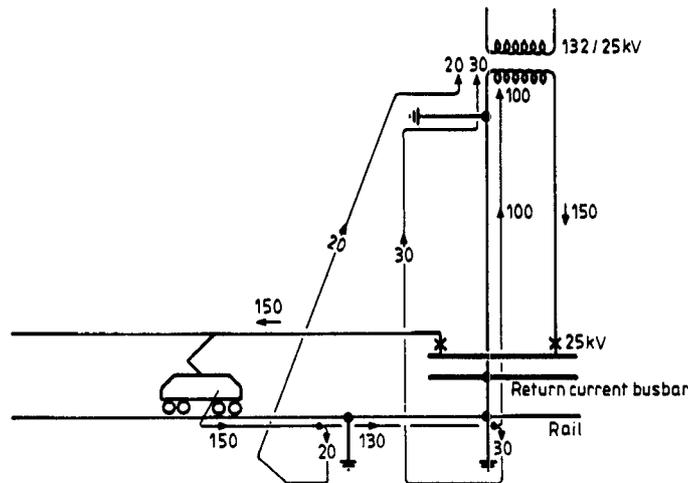
d) Transforming and feeder stations on distant sites. Supply return conductor earthed at the transformer. 25 kV c.b. at transforming station.

**FIGURE 4(c) AND (d): CONNECTIONS FOR VARIOUS TYPES OF SUPPLY POINT**

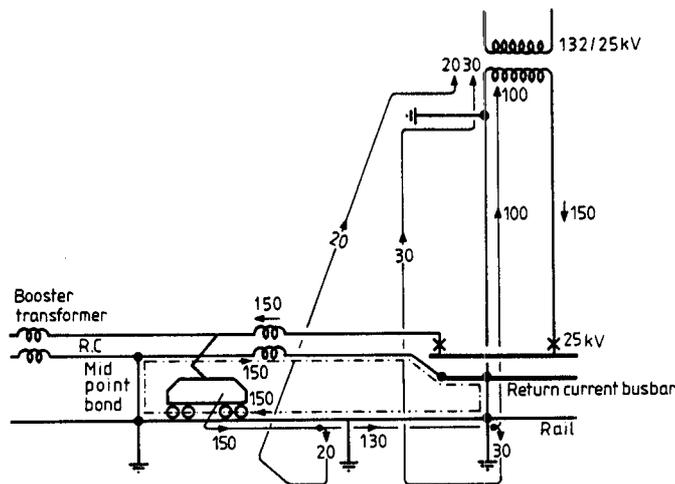


- e) Transforming and feeder stations on distant sites.  
 Supply return conductor earthed at the transformer.  
 Booster transformer in return circuit.

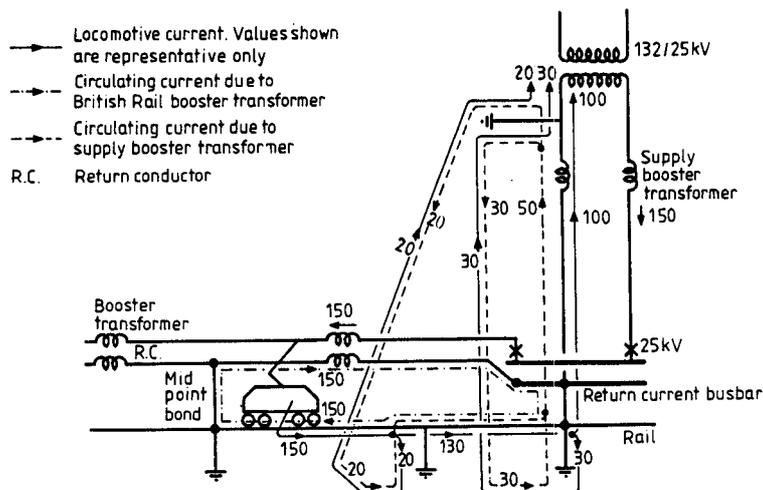
FIGURE 4(e): CONNECTIONS FOR VARIOUS TYPES OF SUPPLY POINT



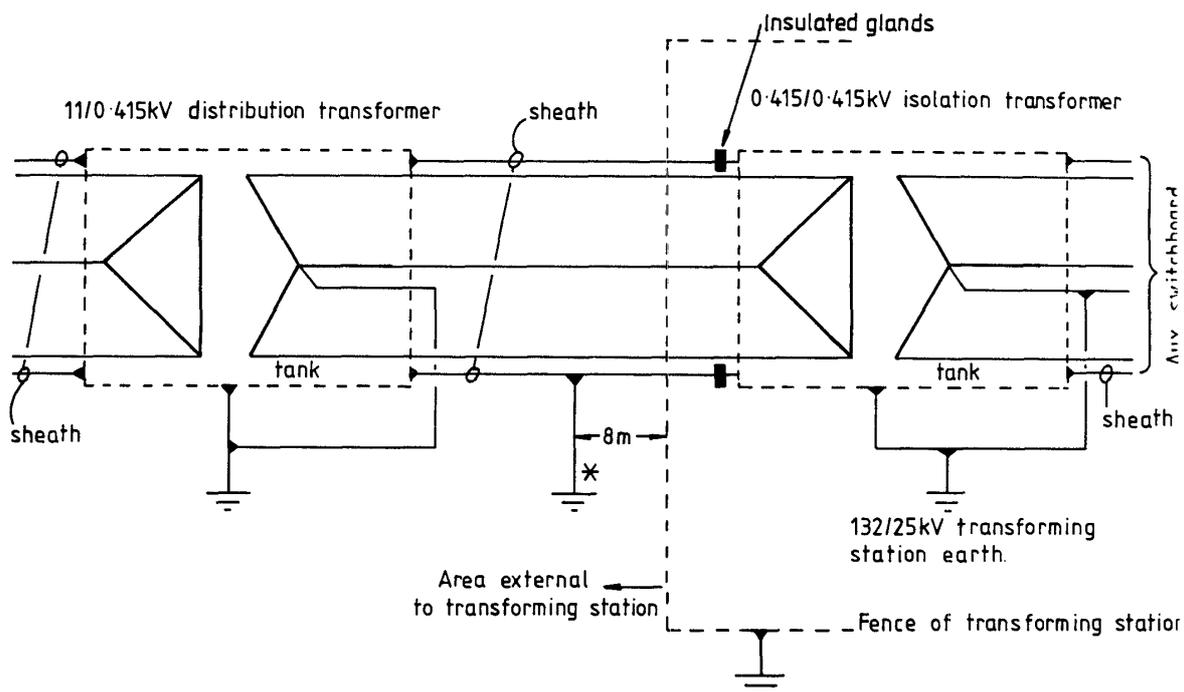
**FIGURE 5: CURRENT DISTRIBUTION – NO BOOSTER TRANSFORMERS**



**FIGURE 6: CURRENT DISTRIBUTION – BRITISH RAIL BOOSTER TRANSFORMER ONLY**



**FIGURE 7: CURRENT DISTRIBUTION – BRITISH RAIL AND SUPPLY BOOSTER TRANSFORMERS**



Three-phase PME system

\* Earth 8m distant from 132/25kV transforming station fence. May not be required if sheath voltage cannot rise to a dangerous level.

**FIGURE 8: 415 V A.C. AUXILIARY SUPPLIES**



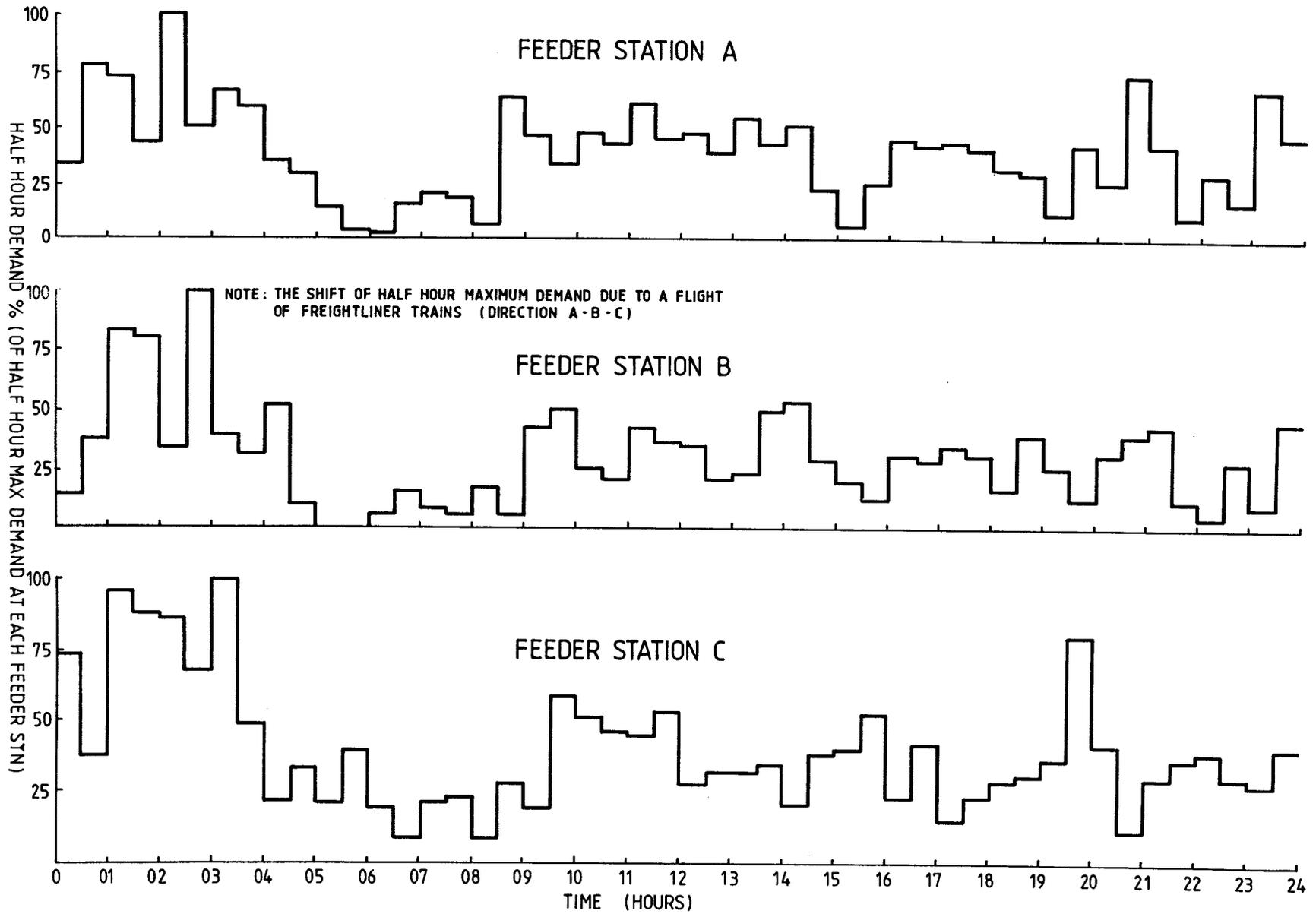
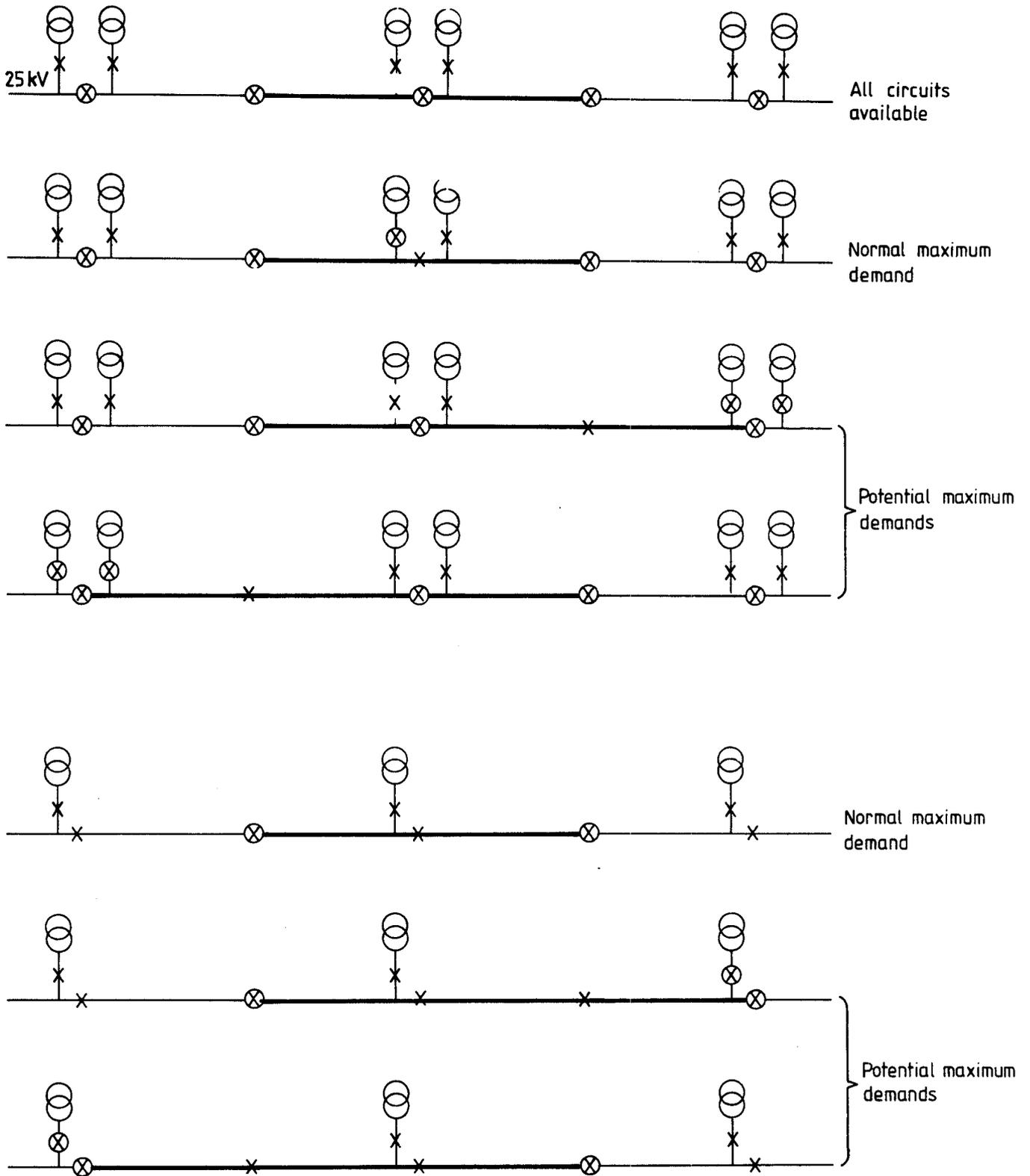
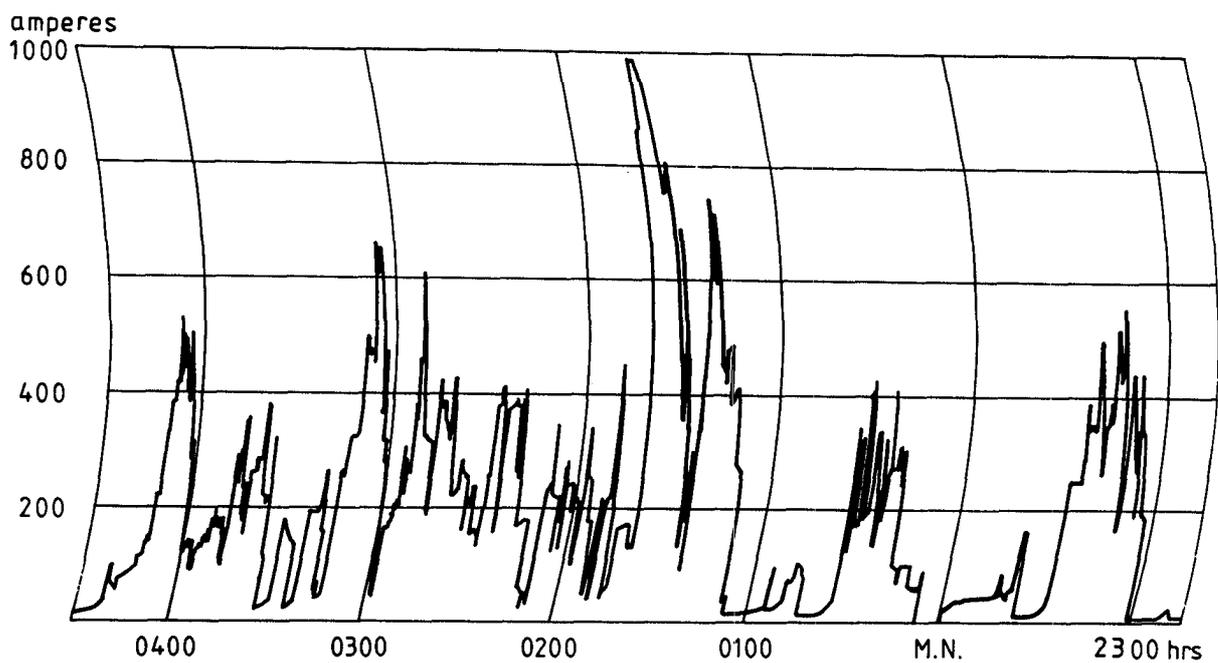


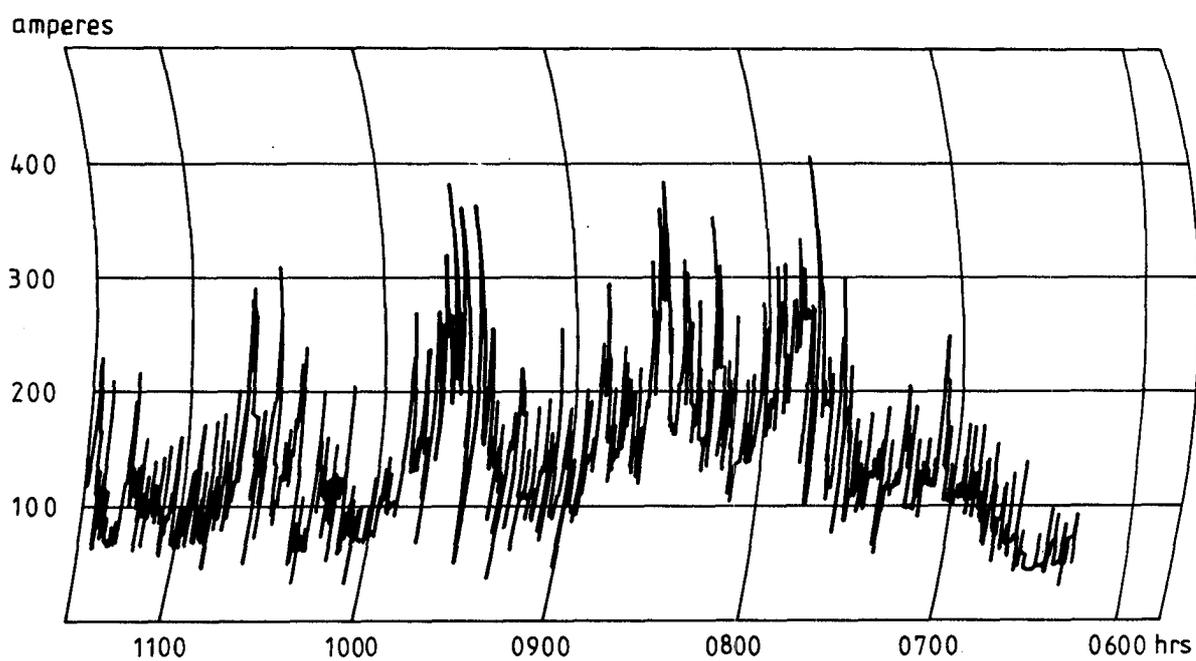
FIGURE 10: TYPICAL DAILY LOAD CURVES – CONSECUTIVE MAINLINE SUPPLY POINTS



**FIGURE 11: ILLUSTRATION OF DEMAND DEFINITIONS AS APPLIED TO NORMAL AND EMERGENCY FEEDING**

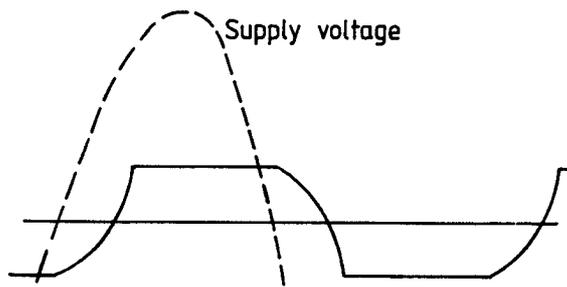


(a) Main Line

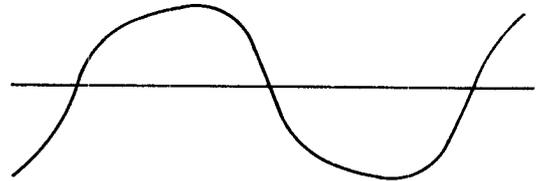


(b) Suburban Line

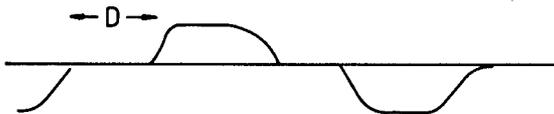
**FIGURE 12: VARIATION IN TRACTION SUPPLY CURRENT**



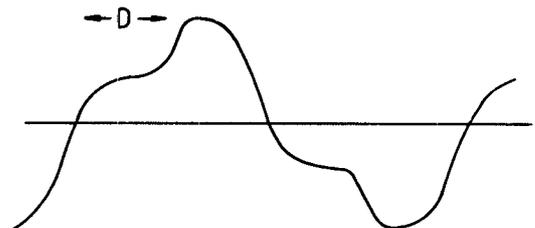
a) Diode locomotive from low load to continuous rating. Occurs frequently, but rarely at the full rated value.



b) Diode locomotive at maximum input power normally used in service. Approximately 25 % greater than continuous rating. Occurs during starting and can persist for up to 2 minutes.



c) Thyristor locomotive at initial starting. Up to rated current. Persists for a very short time.

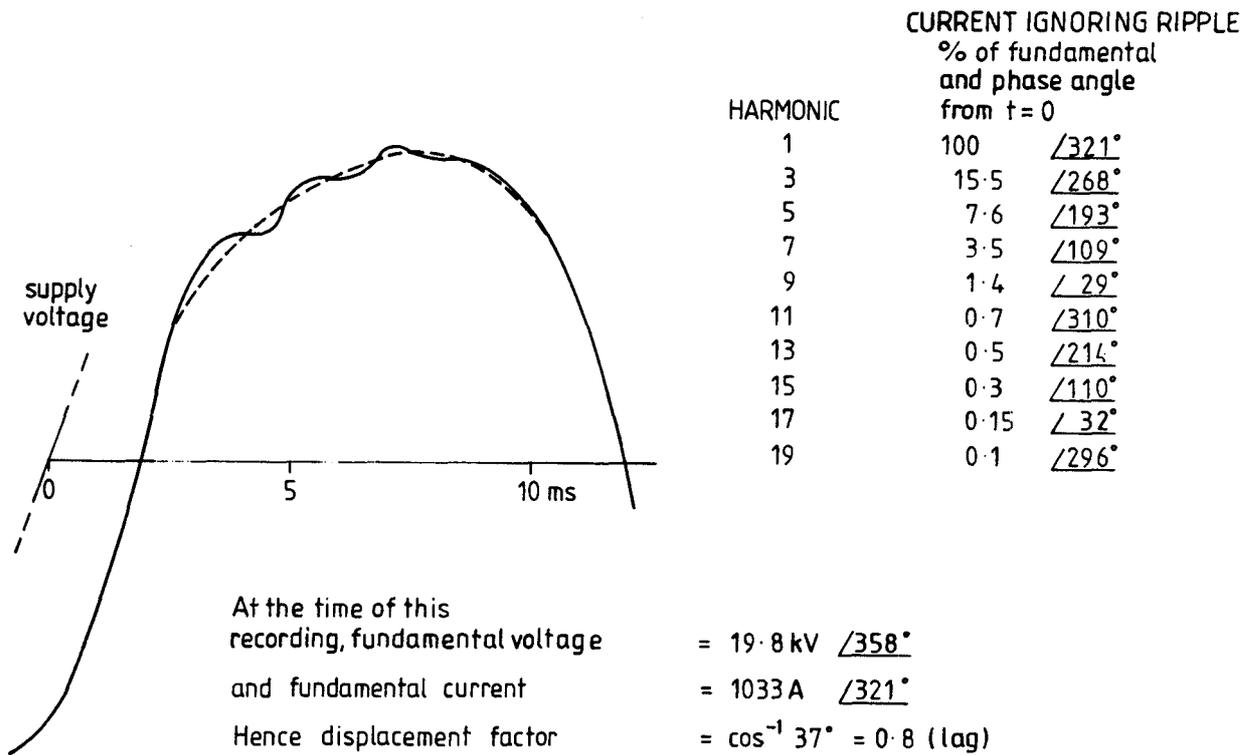


d) Thyristor locomotive at its second stage. Usually during starting. Maximum current persists for a short time.

**NOTES**

a) and b) are typical of locomotives and electric multiple units.  
c) and d) are typical of two-series bridge thyristor control drives.  
Firing delay angle  $D$  is varied between about  $0^\circ$  and  $90^\circ$ .

**FIGURE 13: TYPES OF TRAIN CURRENT WAVEFORM**

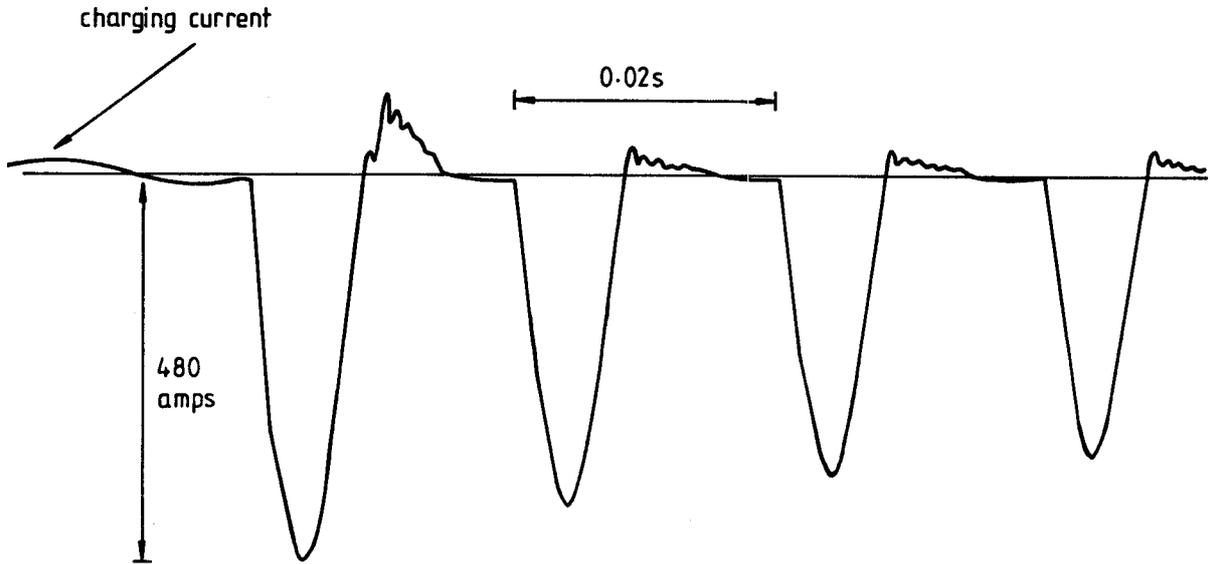


NOTES

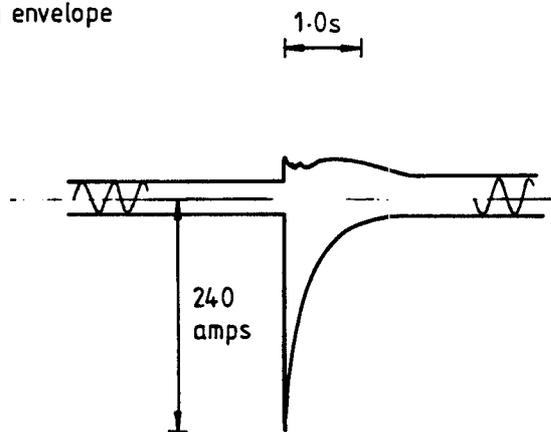
1. All angles are on the particular harmonic's own scale. They are with respect to time  $t = 0$  which is the zero crossing of the complex voltage waveform.
2. The list of harmonics is for the dashed curve which is the estimated shape ignoring capacitance. Harmonics of an order at least as high as any significant resonant frequency on the system should be used.
3. As power factor improves with reduced load the above waveform should be advanced by an angle of  $0.5^\circ$  for every MW reduction below 20 MW. This means an advance of  $n$  times the angle for the  $n$ th harmonic.

**FIGURE 14: SHAPE AND HARMONIC CONTENT OF A TYPICAL SUPPLY CURRENT**

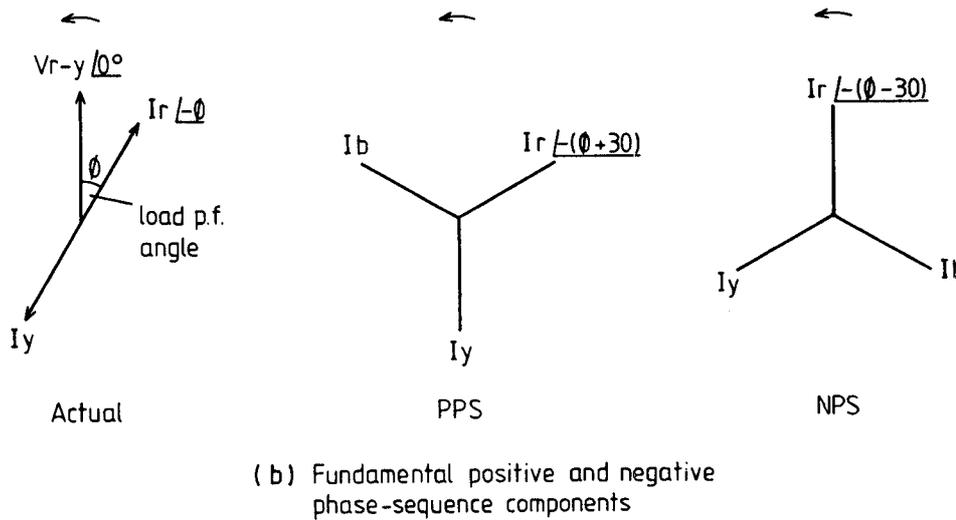
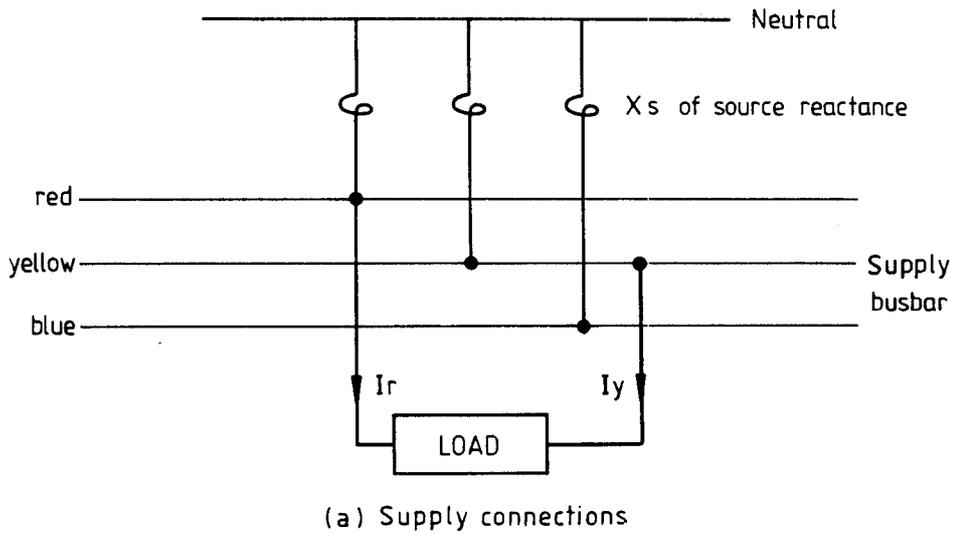
(a) Fast recording



(b) Slow recording, showing envelope



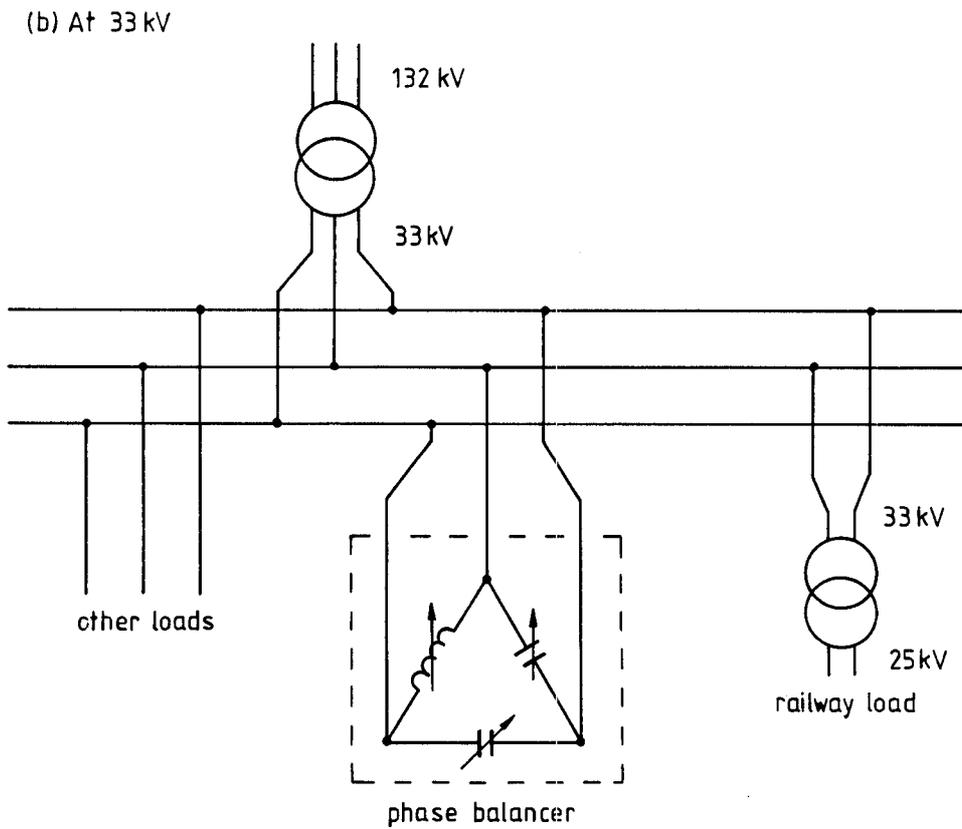
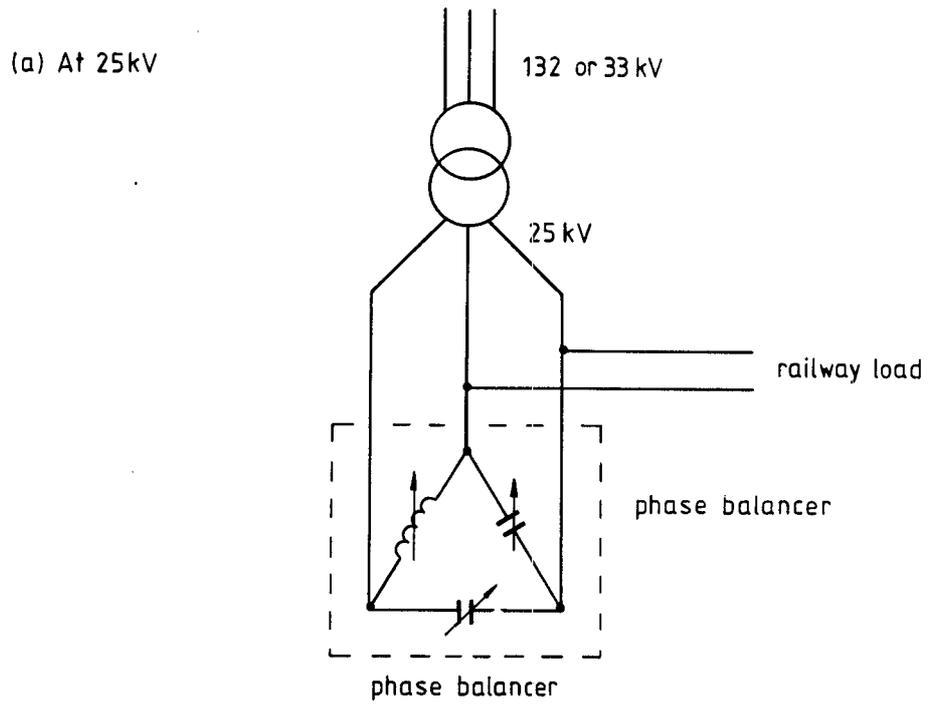
**FIGURE 15: RECORDED EXAMPLES OF LOCOMOTIVE INRUSH CURRENTS**



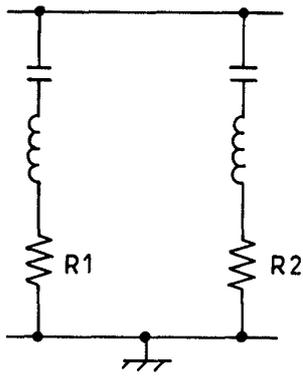
Magnitude of  $I_{r\ pps} = I_{r\ nps} = I_r / \sqrt{3}$ .  
 Nps voltage at supply busbar =  $I_{r\ nps} X_s$ .  
 Expressed as a % of phase-neutral voltage  $V_{nps} \% = 100 X_s I_r / \sqrt{3} \text{ V phase} = X_s I_r / 10 \text{ kV line}$   
 substituting  $(\text{kV line})^2 / \text{Fault MVA}$  for  $X_s$

$$V_{nps} \% = \frac{\text{line-line load MVA}}{\text{Fault level MVA at supply busbar}} \times 100$$

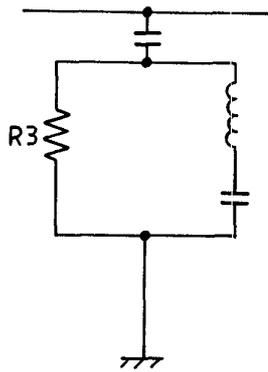
**FIGURE 16: UNBALANCE FROM ONE A.C. TRACTION LOAD**



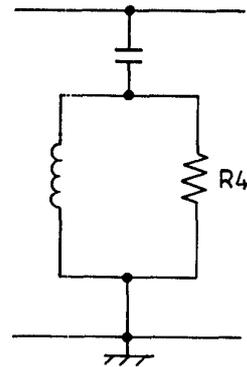
**FIGURE 17: BALANCER APPLICATIONS**



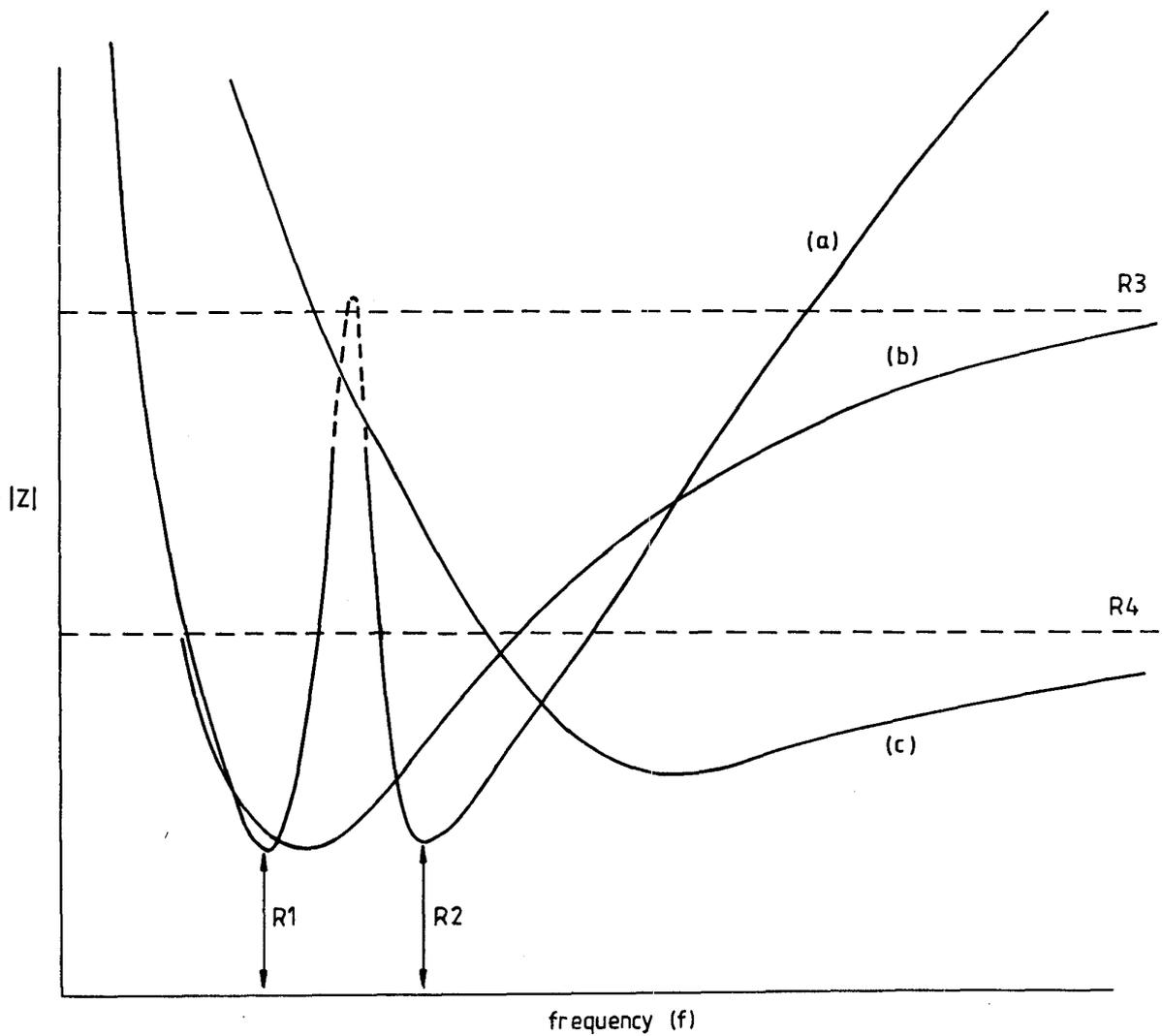
(a) Single-tuned shunt filters



(b) C Type shunt filter  
 3rd order damped

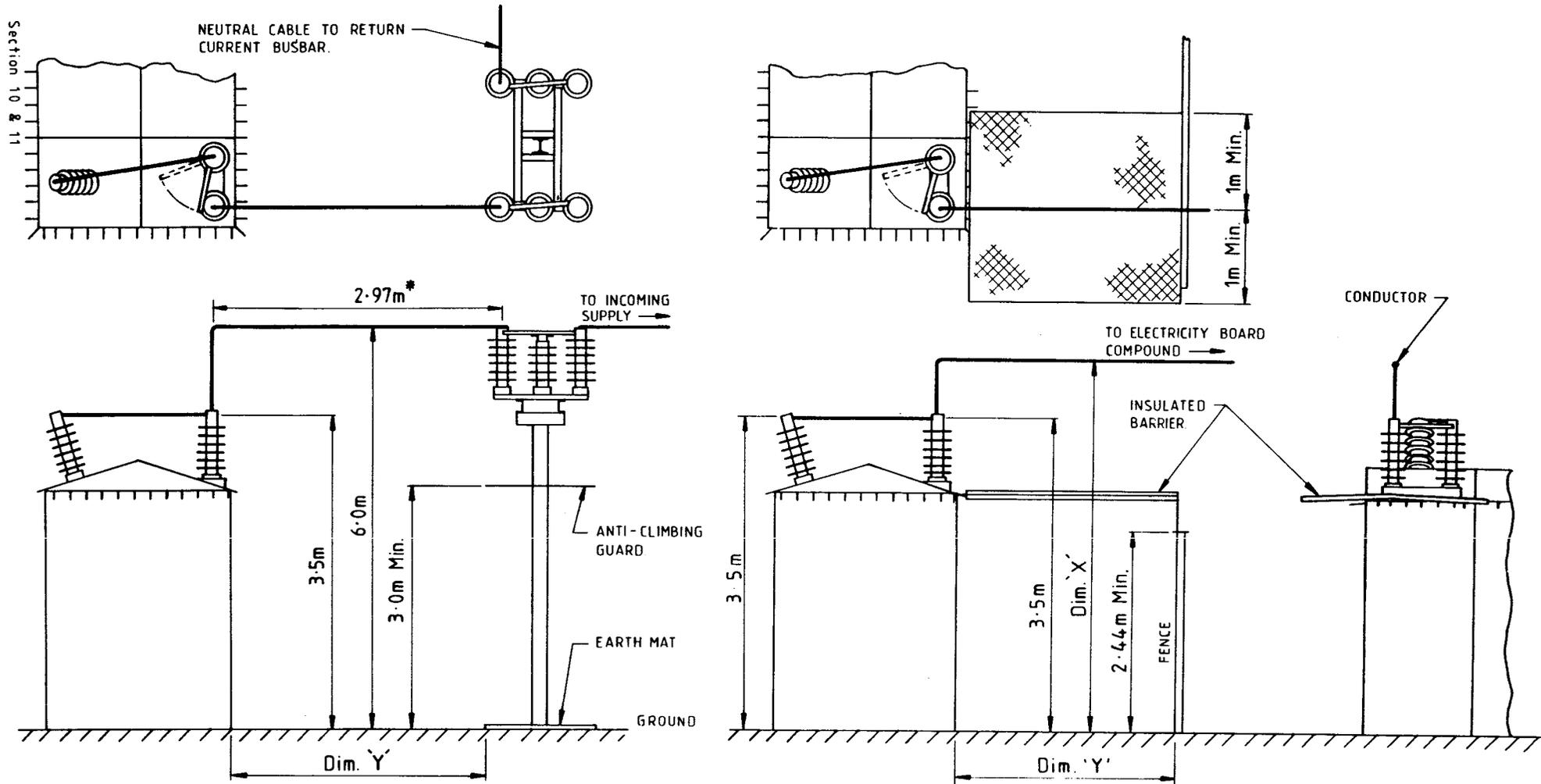


(c) 2nd order damped filter



(d) Filter frequency response

**FIGURE 18: HARMONIC FILTERS**



ARRANGEMENT WITH UNENCLOSED ISOLATOR STRUCTURE.

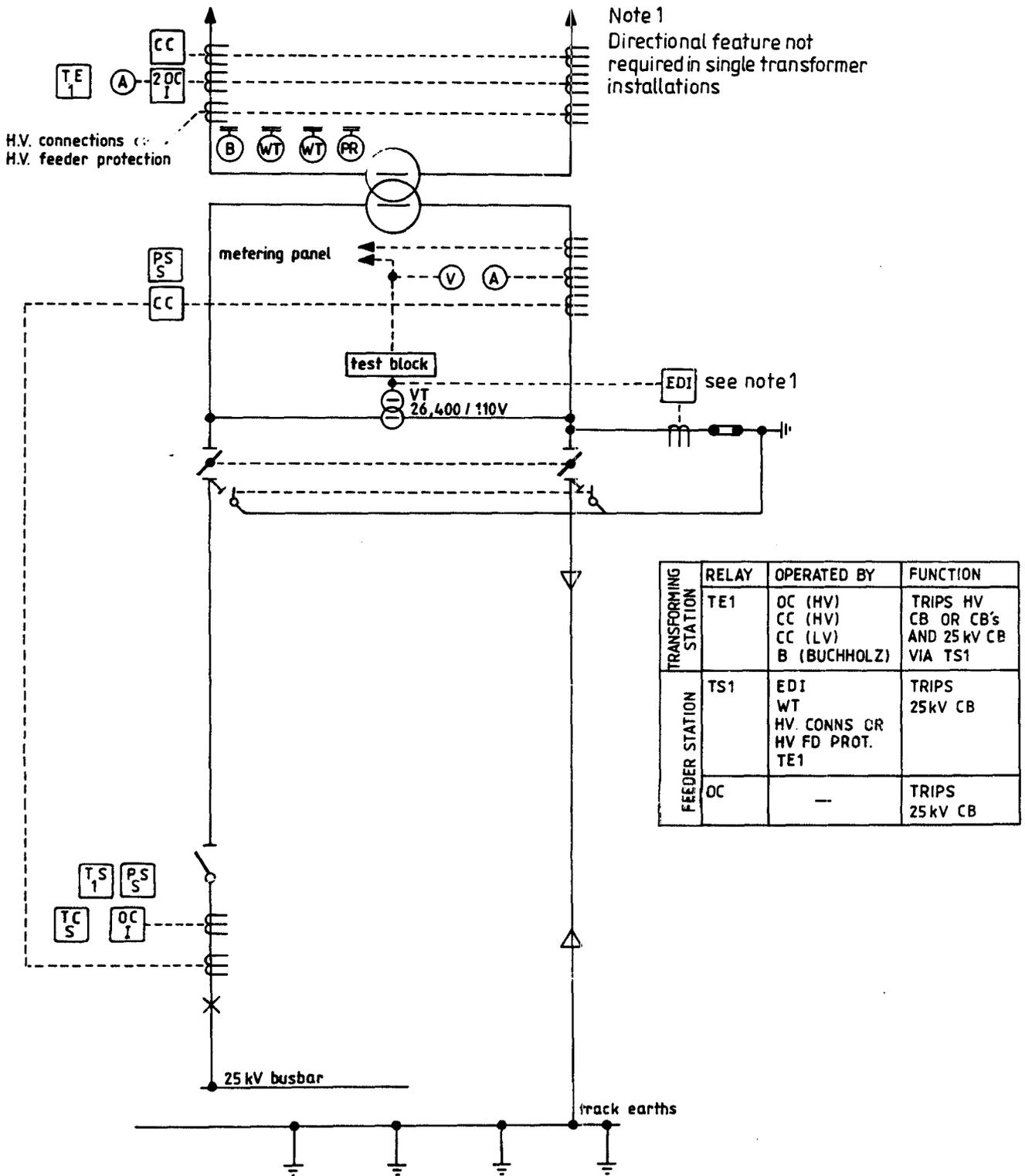
ARRANGEMENT WITH ELECTRICITY BOARD COMPOUND.

\*2.97m TO MEET ELECTRICITY BOARD SAFETY RULES.

DIMENSION 'X' 4.3m MINIMUM (WITH INSULATED BARRIER BETWEEN BUILDING AND COMPOUND FENCE FOR CONDUCTOR HEIGHT OF LESS THAN 6m).

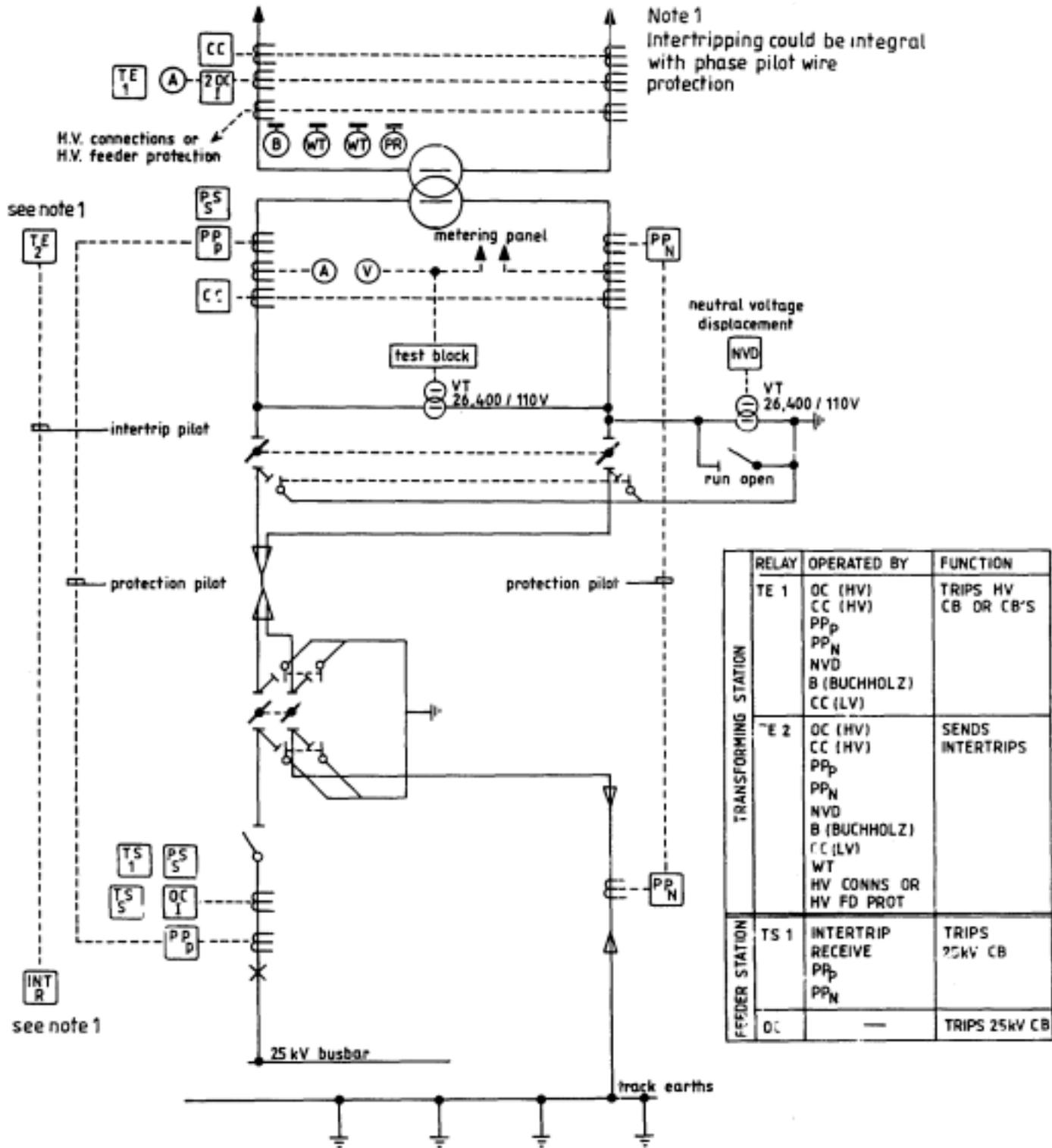
DIMENSION 'Y' WIDTH OF ACCESS DOOR (WHERE APPLICABLE) + 2m TO NEAREST ELECTRICITY BOARD EARTHED METAL

FIGURE 19: 25 kV FEEDER STATIONS ELECTRICAL CLEARANCES



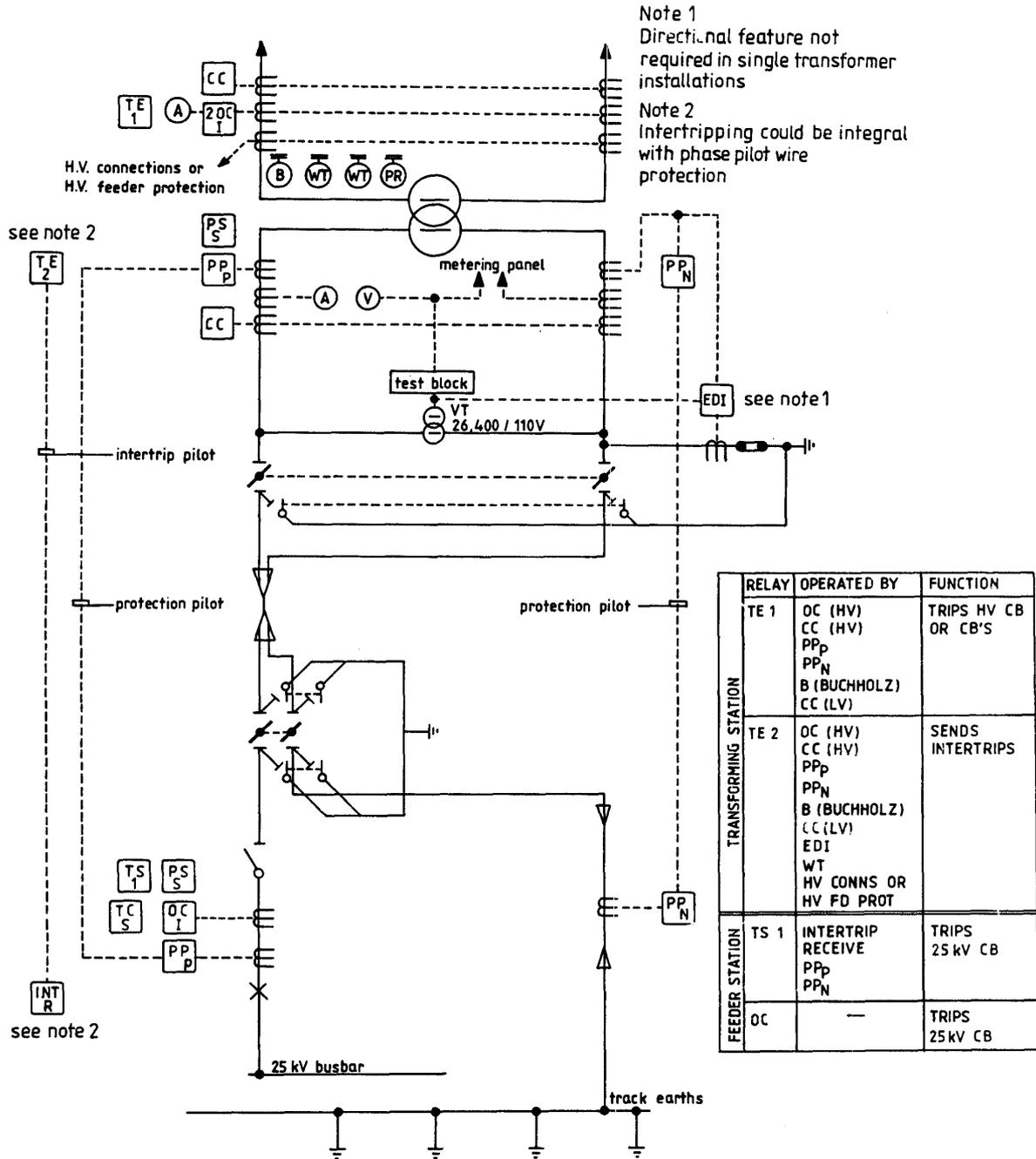
(a) Transforming and feeder stations on same site.

**FIGURE 20(a): PREFERRED PROTECTION ARRANGEMENTS**



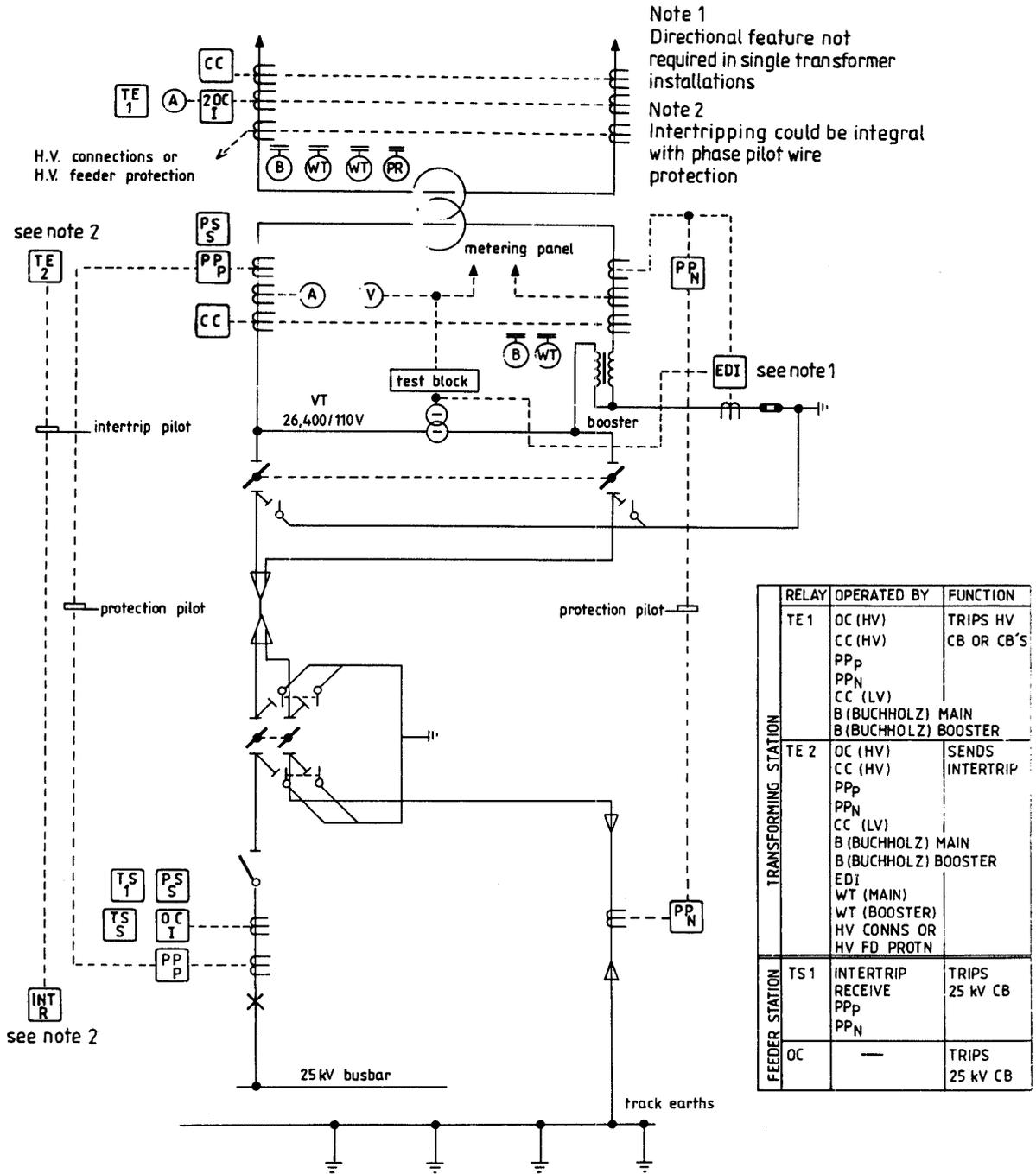
(b) Transforming and feeder stations distant from each other.  
 Supply return conductor unearthed at transformer.

**FIGURE 20(b) PREFERRED PROTECTION ARRANGEMENTS**



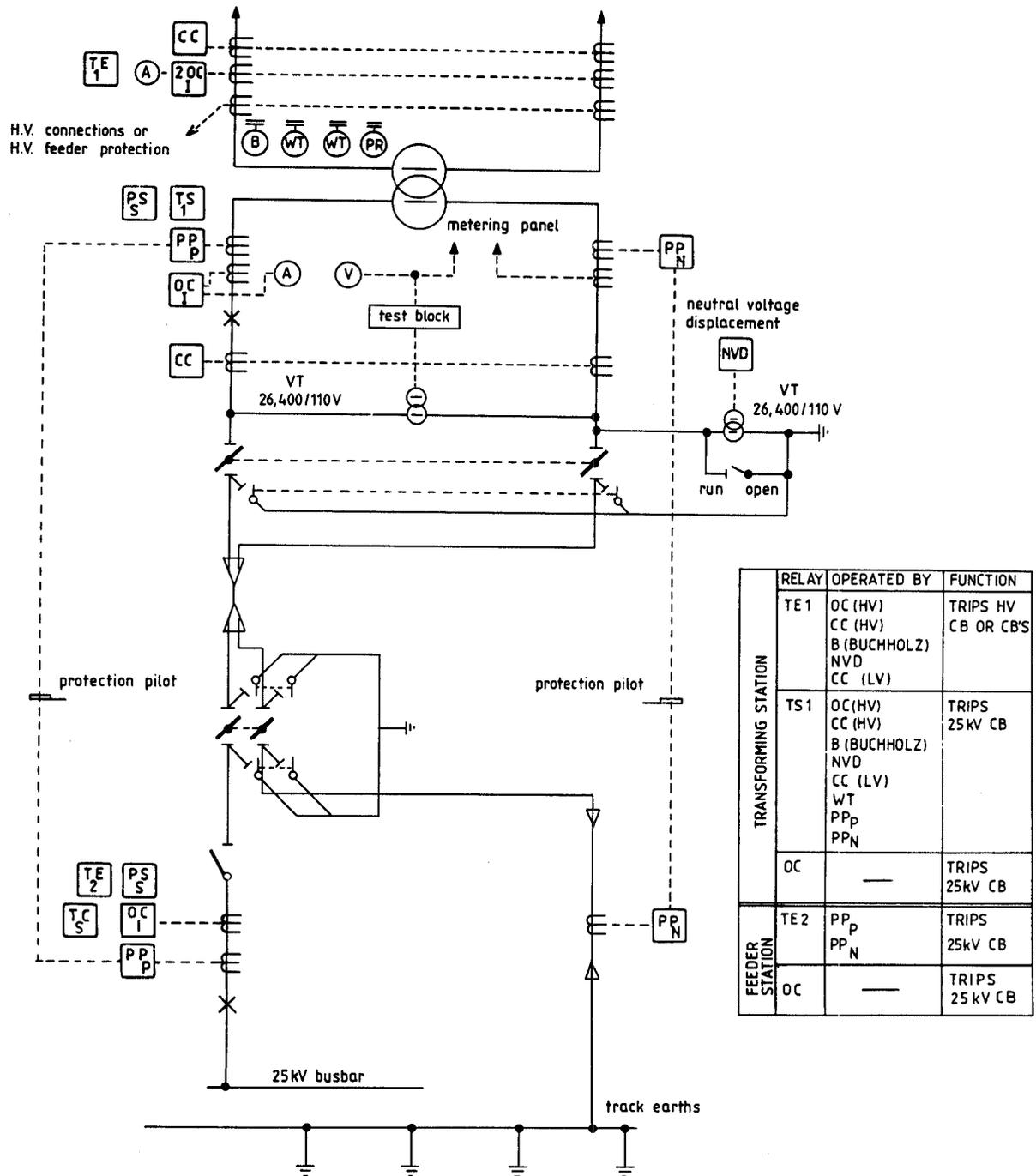
(c) Transforming and feeder stations distant from each other.  
 Supply return conductor earthed at transformer.

**FIGURE 20(c) PREFERRED PROTECTION ARRANGEMENTS**



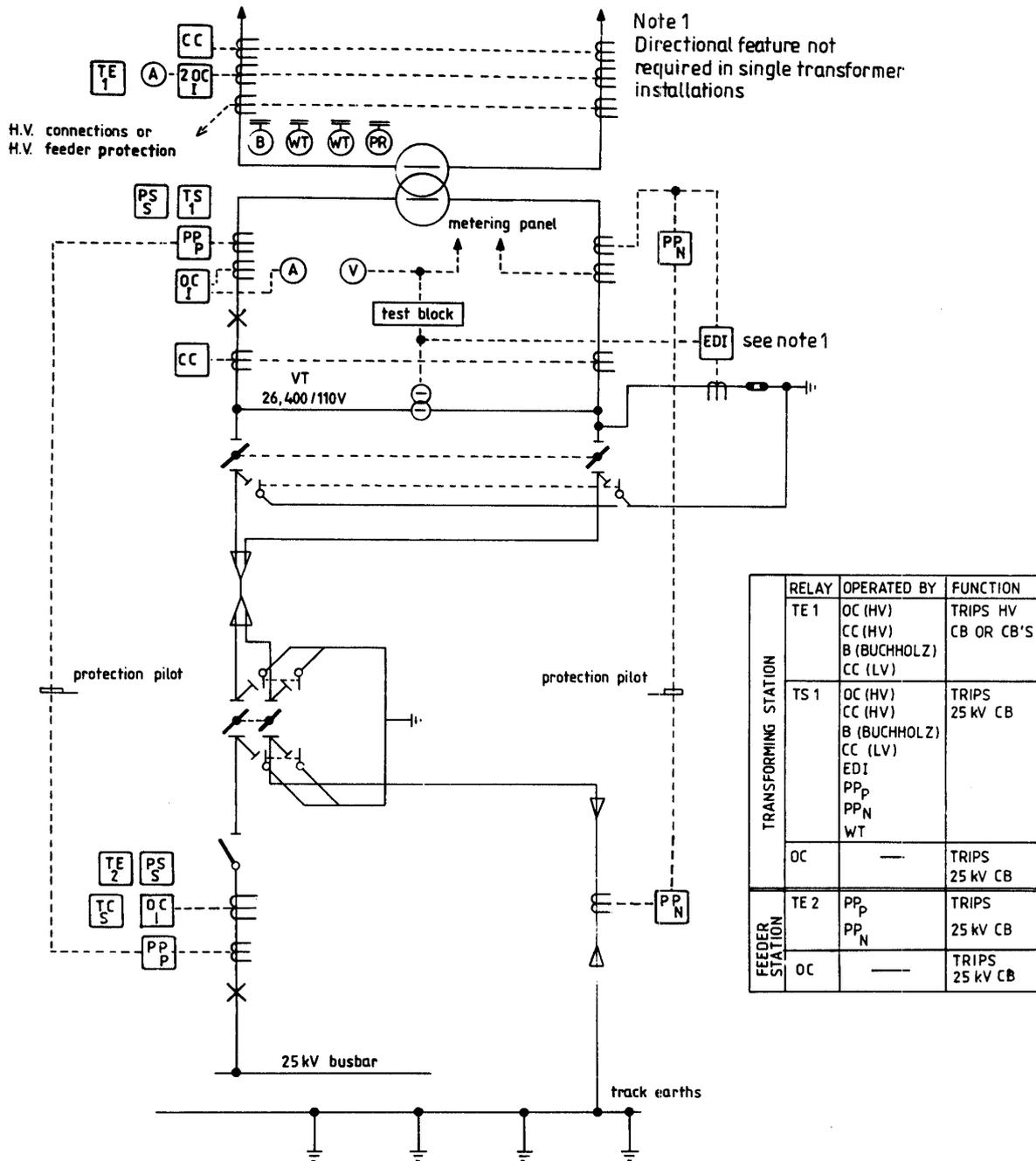
(d) Transforming and feeder stations distant from each other  
 Supply return conductor earthed at transformer  
 Booster in neutral connection

**FIGURE 20(d): PREFERRED PROTECTION ARRANGEMENTS**



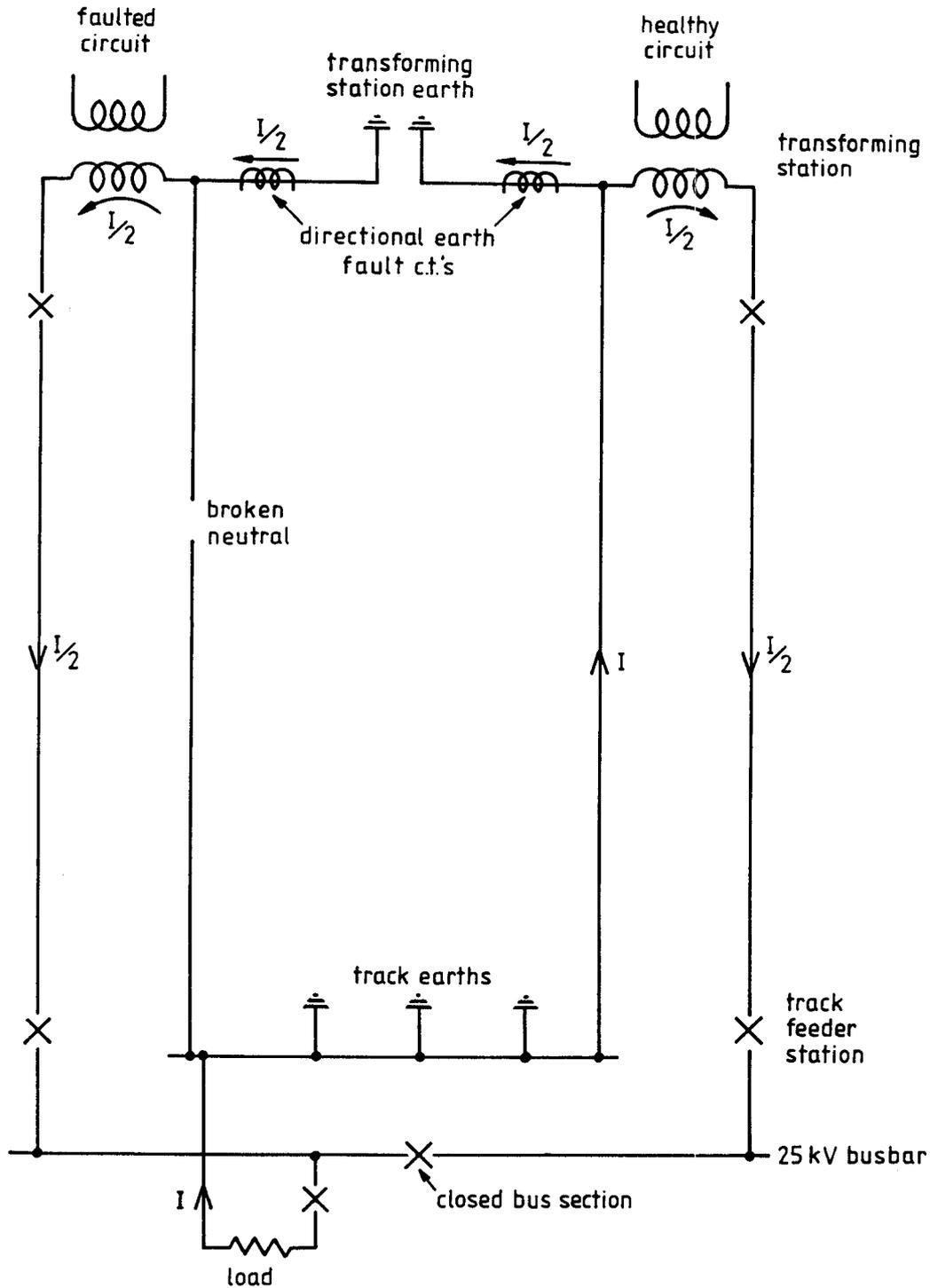
(e) Transforming and feeder stations distant from each other  
 Supply return conductor unearthed at transformer  
 25 kV circuit breaker at transforming station end

**FIGURE 20(e): PREFERRED PROTECTION ARRANGEMENTS**

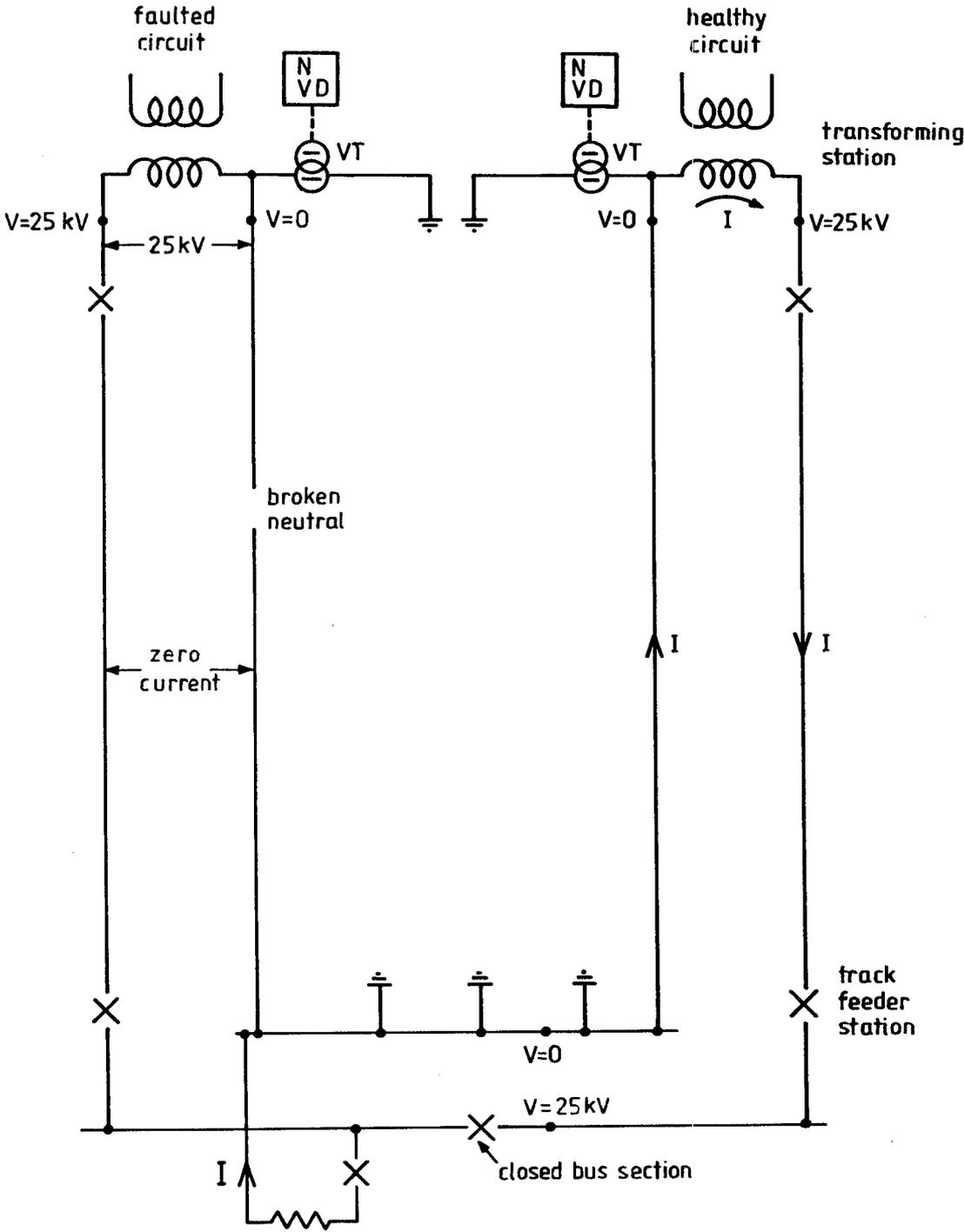


(f) Transforming and feeder stations distant from each other  
 Supply return conductor earthed at transformer  
 25 kV circuit breaker at transforming station end

**FIGURE 20(f): PREFERRED PROTECTION ARRANGEMENTS**



**FIGURE 20(g): BROKEN NEUTRAL CONDITION WITH PARALLELED TRANSFORMERS (NEUTRALS UNEARTHED)**



**FIGURE 20(h): BROKEN NEUTRAL CONDITION WITH PARALLELED TRANSFORMERS (NEUTRALS UNEARTHED)**

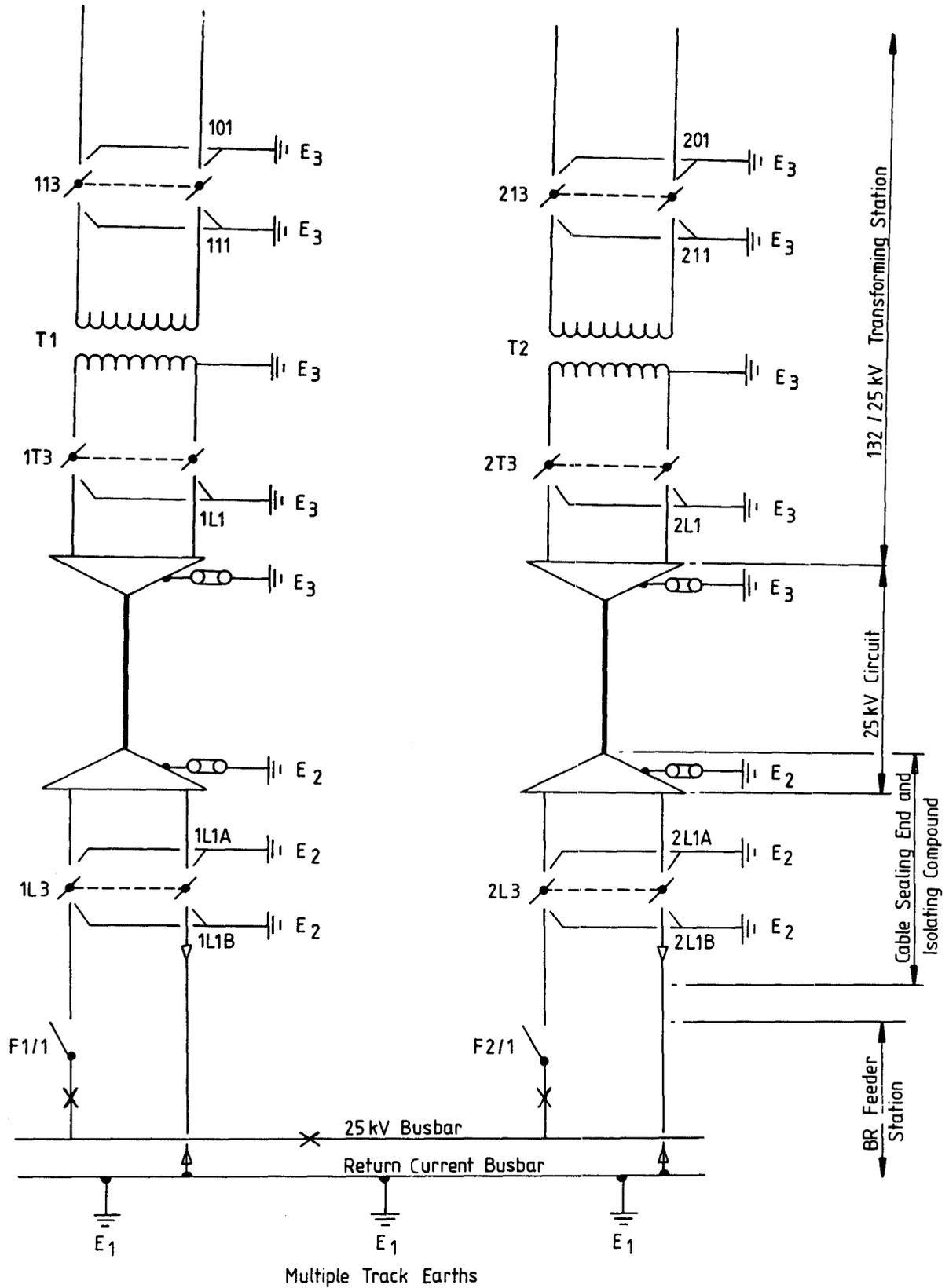


FIGURE 21: EQUIPMENT NUMBERING AT A SUPPLY POINT

## APPENDIX A

### IDENTIFICATION OF WORST DISTURBANCE TIMES

If a detailed load pattern is provided for each supply infeed, it is possible to avoid unnecessary studies by identifying the times when disturbances are likely to be highest.

#### A1. UNBALANCE WITH NO OUTAGE

With only one supply point, unbalance is worst when the traction load is highest. If there are twin transformers connected to different pairs of phases then the worst case is when the sum of their currents added at  $120^\circ$  is a maximum.

For the two loads  $x$  and  $y$  the sum =  $(x^2 + y^2 - xy)^{1/2}$ .

For a number of supply points a simple tabular procedure may be used. The starting point is the load pattern at each supply infeed as illustrated for four infeeds in Table A1. From this, Table A2 shows the total load on each of the three possible phase connections. The last column shows the maximum difference, and the highest value represents the worst unbalance condition which should be studied.

#### A2. UNBALANCE WITH OUTAGE

When a supply point is lost its load is shared by the supply points on each side if possible. Hence unbalance is increased most if the infeed that is lost was on the most lightly loaded pair of phases of the interconnected system. Further, if there are two or more infeeds on this pair of phases, the station taking the highest demand should be assumed lost. This is illustrated in Table A3 compiled from an inspection of Tables A1 and A2. It shows that for this example worst conditions obtain for the loss of infeed B at the first two times and the loss of C during the other two times. Using the same rule as before, time 0.5 minutes still represents the worst condition and would be selected for study. It may also be necessary to examine some of the other times having large numbers in the last column particularly if the local supply point is at the end of the track and hence less affected by other supply points.

#### A3. WORST HARMONICS

Where the supply point has two transformers connected to different pairs of phases it must be remembered that although the two load currents are at  $120^\circ$  they are at  $60^\circ$  in the common phase cable. Hence the  $n$ th harmonic currents in that phase are  $(n 60^\circ)$  apart assuming the two complex waveforms have the same shape. It follows that when the two load currents combine in the common phase their odd triplens will be at  $180^\circ$ , most pairs of other harmonics would be at  $60^\circ$ . To identify the worst case for two currents E and F the rule is:

- (i) Odd triplens, find the highest value of E - F.
- (ii) Even triplens E + F (even harmonics are not normally significant in traction currents).
- (iii) For all other harmonics find the highest value of the vector sum at  $60^\circ$

$$\text{ie } (E^2 + F^2 + EF)^{1/2}.$$

When there are a number of supply points experience shows that the highest harmonics result from a particular pair of adjacent infeeds, hence the above rules can be used. For the example in Table A1 the worst triplens are to be expected at time 1.5 between stations B and C where the difference, 9 - 2, is the highest of any adjacent pair. For other harmonics the highest pair added vectorically is clearly C and D at time 0.5. Harmonic levels at both these times should be assessed. It is quite often found that worst conditions for n.p.s. are the same as for worst harmonics, in which case both conditions are calculated simultaneously in the study.

**TABLE A1 EXAMPLE OF DEMANDS DURING NORMAL RUNNING**

MVA demands at supplies A-D off phase colours shown.

Time Mins.	A r - y	B y - b	C b - r	D r - y
0.5	10	6	12	7
1.0	8	4	5	6
1.5	5	9	2	6
2.0	7	8	7	3

**TABLE A2 IDENTIFICATION OF WORST CASE**

The worst unbalance case is found by adding the loads on each particular pair of phases and then finding the time of greatest overall unbalance:

Time	on r - y	on y - b	on b - r	Maximum Difference
0.5	17	6	12	11 worst case
1.0	14	4	5	10
1.5	11	9	2	9
2.0	10	8	7	3

Hence the conditions at time 0.5 should be studied.

**TABLE A3 DEMANDS DURING WORST OUTAGES**

Time Mins.	A r - y	B y - b	C b - r	D r - y	Maximum Difference On Any Phase Pairs
0.5	13	out	15	7	20 (ie, A + D - B)
1.0	10	out	7	6	16
1.5	5	10	out	7	12
2.0	7	11.5	out	6.5	13.5

## APPENDIX B

### HARMONIC AND UNBALANCE STUDY DETAILS

#### B1. STUDY PROCEDURE

For a power system study, using HARP03, the following seven steps are required. A new version, HARP04, is available to automate the steps into a single study and to derive the injected currents for step 4.

Set up the per-phase representation of the lines and loads in the usual way.

Refer to this as red phase and make two further sets with changed station names for yellow and blue phases. Note that this three-phase representation is essential for harmonic studies as they involve line-to-line capacitances. The results at fundamental frequency are easily converted to negative phase-sequence voltages even though a single-phase study would have been sufficient for these.

Include the line-line transformers; it is convenient to insert half the nameplate reactance in each phase. The lumped value of 25 kV capacitance and any balancer equipment impedance should be connected across the appropriate phase pairs.

List the injected harmonic currents and phase angles in each 25 kV phase at each supply point. For each individual load, the currents in one 25 kV terminal will be the inverse of the currents in the other. Phase angles should be quoted with respect to a red phase voltage at one selected red-yellow supply point. An allowance should be included for any phase displacement across the system due to normal three-phase power flows.

If the injected harmonic currents are based on the assumption of a purely inductive system as described in Section 6, it would be necessary to determine the effect of the network capacitances and in particular those of the 25 kV circuit on the harmonic currents drawn from the supply system. This requires that some representation of the railway supply point be included as described below. A preliminary study should be made with all resistance and capacitance removed and with the harmonic currents injected via the equivalent reactance representing the 25 kV contact wire and locomotive transformers.

From this study the voltages calculated at the point of current injection, are with respect to the three-phase neutral and the difference at each pair of terminals, represents the equivalent rectifier voltage. This would not be significantly changed when the network capacitances are introduced. Then if the study is repeated applying the derived line-to-line voltages with system capacitance and resistance inserted, the effect of these on the harmonic behaviour of the network is realistically included. From this second study an estimate of the harmonic currents and voltages throughout the network can be obtained.

Calculate the negative phase-sequence components for any three-phase currents and voltages at fundamental frequency.

Repeat steps 5 to 7 for outage conditions being studied. If the circuit outage does not significantly affect the impedance conditions as seen from the 25 kV terminals of a railway

supply transformer, it would not be necessary to redetermine the equivalent rectifier voltage for that location. Any change in assumed railway loading conditions would require recalculation of the equivalent rectifier voltage for that location and for others.

## **B2. REPRESENTATION OF THE 25 kV SYSTEM**

Comparative tests have shown that for estimating effects in the Supply Authority network, a simple equivalent may be substituted for the 25 kV system at each feeder station bus-section. This equivalent consists of a single capacitor, at the feeder station, for the total 25 kV capacitance where the sum of the train currents is injected via a single inductive commutating reactance.

This simplification is possible mainly because the overhead track circuits are interconnected at track sectioning cabins thereby effectively reducing the overhead line circuit inductance seen by any locomotive due to the parallel circuits. Hence the effective value of the line inductance is significantly smaller than the locomotive transformer inductance so that it is reasonable to lump the distributed capacitance of all the overhead lines. It is convenient to assume this is located at the supply point and little error is introduced by this assumption.

However it should be pointed out that this simplified representation is not suitable for detailed examination of conditions on the 25 kV track sections. For this it would be necessary to represent fully each separate train and use a distributed line representation of the overhead line equipment.

The representation for supply network studies is illustrated here by means of examples using typical values for transformer and line reactances etc.

A 10 km length of single track and booster transformers typically has an impedance of  $3.0 + j8.0$  ohms or  $48 + j128\%$  on 100 MVA base. The capacitance of a 10 km length is about 0.1 micro F. This representation is therefore as shown in Figure B1 for a red-yellow supply to a locomotive via the 10 km section where:

$Z_t$  is the supply transformer nameplate impedance.

$X_c$  is the 25 kV circuit reactance.

$X_1$  is the locomotive transformer reactance, typically 384%.

$I_n / \angle \phi^\circ$  is the fundamental or any harmonic current in the pantograph on the phase feeding; the contact wire (usually the leading phase).

For a representative example of full load, a feeder station is assumed to feed 40 km of double track joined together at 10 km intervals i.e. at each end, at the MPTSC and at the ITSCs. Four locomotives are assumed at 10 km intervals and the arrangement is therefore as shown in Figure B2.

On the basis that each train can be considered as a source of current harmonics being injected via its rectifier transformer, it is possible by the application of Thevenin's theorem to derive a single equivalent current source and network equivalent impedance. The current source,

being the sum of the individual currents, can be represented by a suitable total current waveform for the supply point as illustrated in Figure 14.

The equivalent reactance is that calculated to the terminals of the supply transformer with all the rectifiers short circuited. This is shown in Figure B3 for the component values shown in Figure B2. In practice the effective value of the equivalent reactance does not vary significantly with practical changes in position of the locomotives.

For the special case of a single point there is no need to consider more than one phase. Only half the reactances  $X_1$ ,  $X_c$  and the equivalent (shown in Figures B1, B2 and B3) would be used to bear the correct proportion with the single-phase impedances of the supply network. In a single-phase study, the overhead line capacitance would have to be represented as an equivalent capacitance to neutral which would be twice the actual capacitance i.e. 0.02  $\mu\text{F}$  per track km. In this case the British Rail overhead line and any other line or cable could be represented by the exact pi equivalent to neutral that is created by HARP program.

### **B3. NETWORK VOLTAGE LEVELS**

Problems can occur in the calculation of actual network voltage levels at fundamental frequency where a number of transformation stages are involved and different vector groupings are employed. The method of dealing with this is illustrated for the example shown in Figure B4 which shows a one-line diagram of a supply system unbalanced by a pair of line-to-line traction loads. These loads could be the actual values at a particular time or, if voltage step changes are sought, the sudden load changes that could occur. It is required to know both the line and phase voltages at each busbar from 132 kV down to 415 volts. The representation in HARP and the data to be quoted are shown in Figure B5. Although only one transformer is shown between busbars, its impedance is that of the actual number in parallel passing the stated load.

It is not necessary here to represent the entire supply system in detail; a single impedance may be used for each phase of the source. It can be derived from the known three-phase fault reactance as follows. A large part of the fault reactance is in the lines and transformers back to the generator terminals. A special national fault study showed that at least 90% of the 132 kV fault reactance is in the lines and transformers. At 400 kV substations, the figure could be 75% remote from generation but down to 50% near generation. The remainder represents all generator sub-transient reactance and it need not be modified if the negative phase-sequence component or harmonics in busbar voltages are being calculated. If sudden voltage changes, e.g. flicker, are being calculated then the generator sub-transient reactance should be multiplied by (say) 1.7 to represent the transient reactance. If slower voltage changes or drifts are being calculated then the generator reactance should be put at zero.

The results would need adjustment if HARP is used as it does not directly allow for phase shifts caused by star-delta or delta-star transformers. This is dealt with by drawing the phasing diagrams in Figure B4 which shows the voltages given by HARP on the red phase for example. As seen they could be phase or line voltages, depending on the transformer vector group, but being expressed as percentage of the nominal phase or line voltage both will be given as about 100%. By inspection of the phasing diagrams the colours can be allocated to the results.

A separate calculation would convert phase voltages to line voltages, by finding the vector difference of appropriate pairs. Given line voltages, the phase voltages are found from:

$$\begin{aligned}r &= [(R-Y) - (B-R)] / \sqrt{3} \\y &= [(Y-B) - (R-Y)] / \sqrt{3} \\b &= [(B-R) - (Y-B)] / \sqrt{3}\end{aligned}$$

#### **B4. EXAMPLE**

The details of an a.c. traction supply system are shown in Figure B6 with load levels based only on preliminary estimates. The supply point at station C is on a separate source network, e.g. a 275 kV system. This station is tested by injecting the peak demand but for the rest of the system the peak demand should be assumed only at one supply point in any one study, in this case station G. As recommended, the peak demand is taken as twice the highest half-hour average.

To illustrate worst case conditions, a second emergency outage is considered by removing the two transformers shown at station E/F. Most of the load on section E is transferred to section D and most of the load on section F is transferred to section G, as maximum loads are not simultaneous. Table B1 shows the assumed MW load at each station in consequence. Dividing by displacement factors appropriate for the load level gives the MVA demand. The table also shows the fundamental current converted to % on 100 MVA base as used in studies to be comparable with the units of V% and X% on 100 MVA base.

All feeder station current waveforms are assumed to have the same rounded shape as in Figure 14. The fundamental and harmonic current at station C is quoted as a master hence at each other station the harmonics have the same proportion to the fundamental. Current amplitudes are therefore as shown in Table B2. Phase angles for the nth harmonic in the table are calculated from those quoted for station C using the following formulae:

$$\begin{aligned}\text{If R-Y supply, angle at station C} &+ nA^\circ \\ \text{If Y-B supply, angle at station C} &+ n(A^\circ + 240^\circ) \\ \text{If B-R supply, angle at station C} &+ n(A^\circ + 120^\circ)\end{aligned}$$

angle A has two components as illustrated in table B1:

- (i) The system phase angle due to other power flows and is derived from a 50 Hz load flow study.
- (ii) The difference in the displacement (or power factor) angle.

As vectors are assumed to rotate anti-clockwise in HARP, the system phase angle at a station is positive if the station is ahead of the master station. Also, if the displacement angle at the station is lower than that at the master station then the relative displacement angle is positive.

These currents are injected into a three-phase representation of the supply network shown in Figure B7 with all resistance and capacitance temporarily removed. The resulting voltage drops on the system are given by the program; those at fundamental frequency are needed for unbalance estimates and those at harmonic frequencies are needed for input to a second study

for harmonics. The calculated fundamental voltage drops are given in Table B3 and their negative phase-sequence components have been calculated from the usual formula:

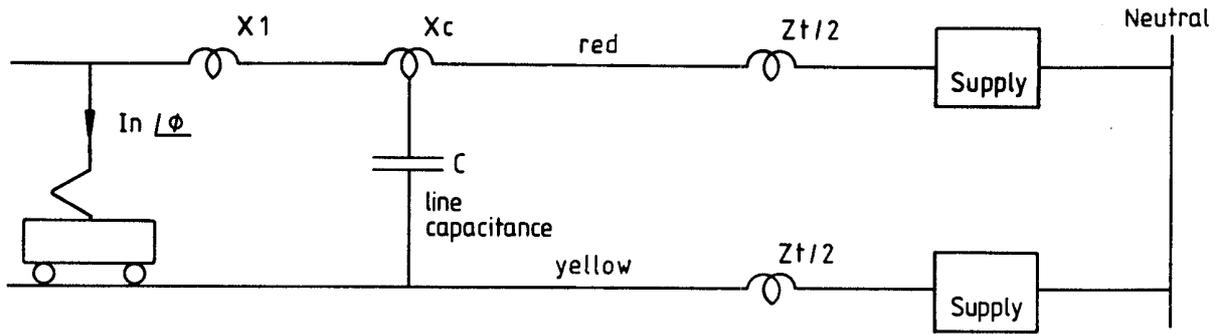
$$(V_r + V_y \text{ back } 120^\circ + V_b \text{ forward } 120^\circ) / 3$$

As seen, the 0.7% n.p.s. voltage level at the isolated station C, could have been more simply calculated from 7 MVA load x 100/1000 MVA fault level.

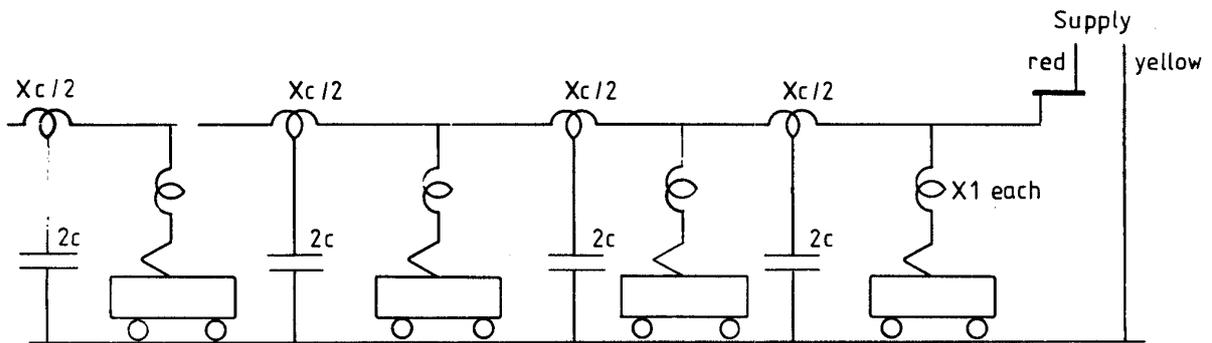
To estimate the modification of the effective railway load current, as a result of resonance in the supply network, a second study is made with all capacitance and resistance included. For this study the line-to-line harmonic voltage at the equivalent rectifier terminals as derived from the first study is used as the driving function. The traction harmonic currents may now be different from those used for the first study if the effect of circuit resonance is significant. In the example shown parallel, resonance occurs at near 7th harmonic on the h.v. section of Station C due to the assumed 20 MVAr of capacitance in the h.v. system. The effect can be seen by comparing the values of  $I_c$  in tables B2 and B4 and on the harmonic voltages on the h.v. side of the transforming station where the 7th harmonic voltage is high at 2.6%. If the rectifier Current had not been corrected the 7th harmonic voltage would have been unrealistically high at 3.6%.

Table B4 also shows the harmonic voltages at point D where the general level is higher due to the increased magnitude of the railway load. However, at D there is no magnification at 7th but some enhancement of the level at the 11th harmonic. This can be explained by the different impedance values in the h.v. circuit.

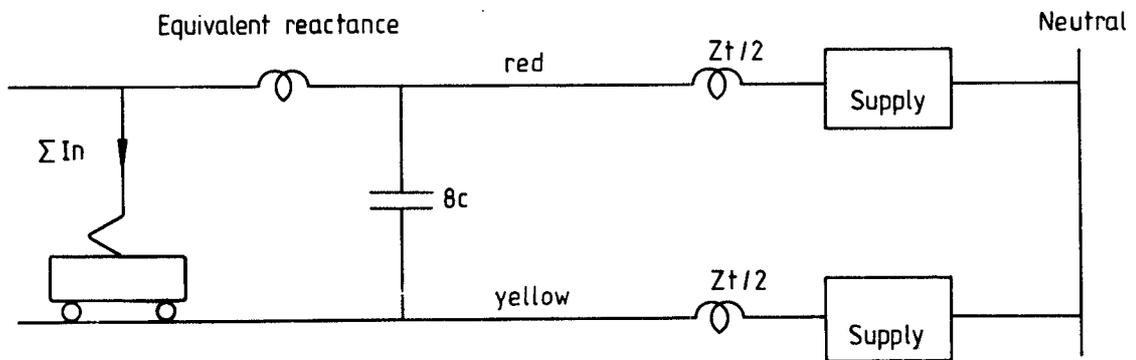
The harmonic composition of the railway load current can also be modified by resonance associated with the 25 kV circuit capacitance. However, the resonant frequencies tend to be higher, above 20th harmonic if there is no 25 kV cable connection to the transforming station falling to near 11th harmonic for the longer lengths of cable.



**FIGURE B1: SUPPLY TO SINGLE TRAIN ALONG 10 km SINGLE TRACK**



**FIGURE B2: SUPPLY TO FOUR TRAINS ON 40 km DOUBLE TRACKS**



**FIGURE B3: EQUIVALENT OF FIGURE B2**

Note: (Figures B1, B2 and B3)

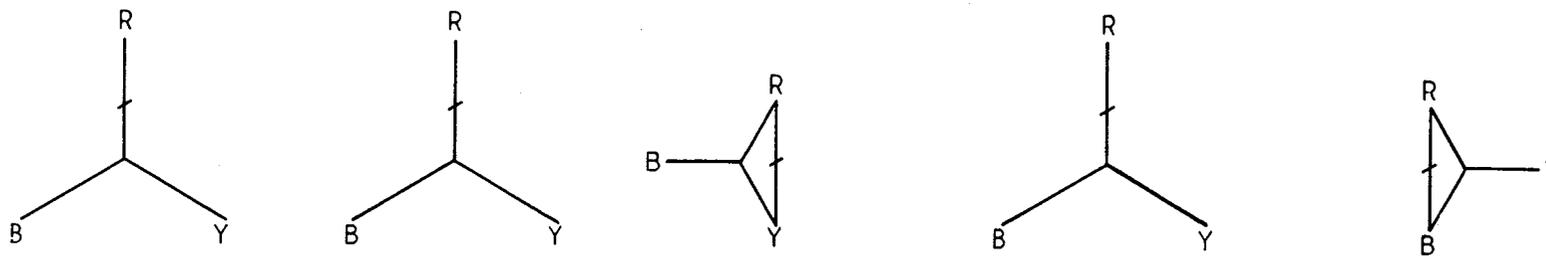
In this example :

$$X1 = 384 \%$$

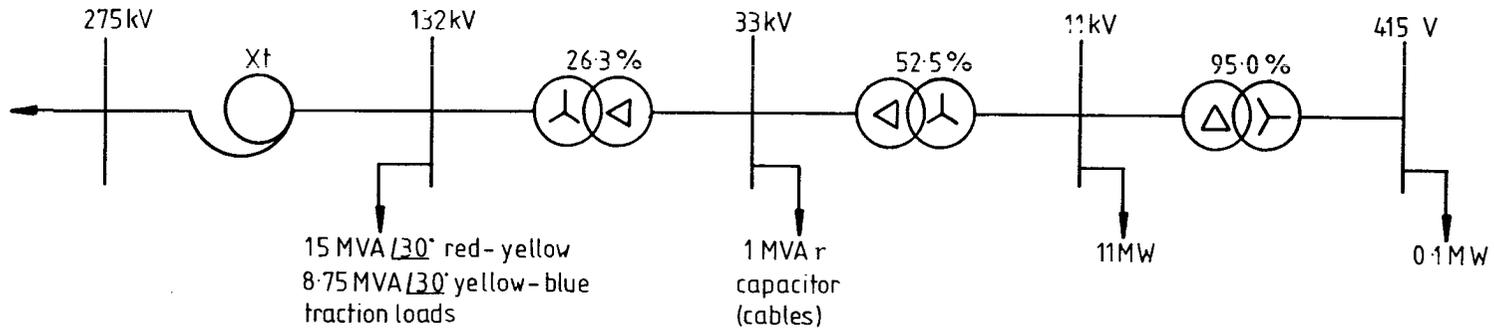
$$Xc = 128\%$$

Equivalent reactance = 137 % (with loco rectifiers short circuited)

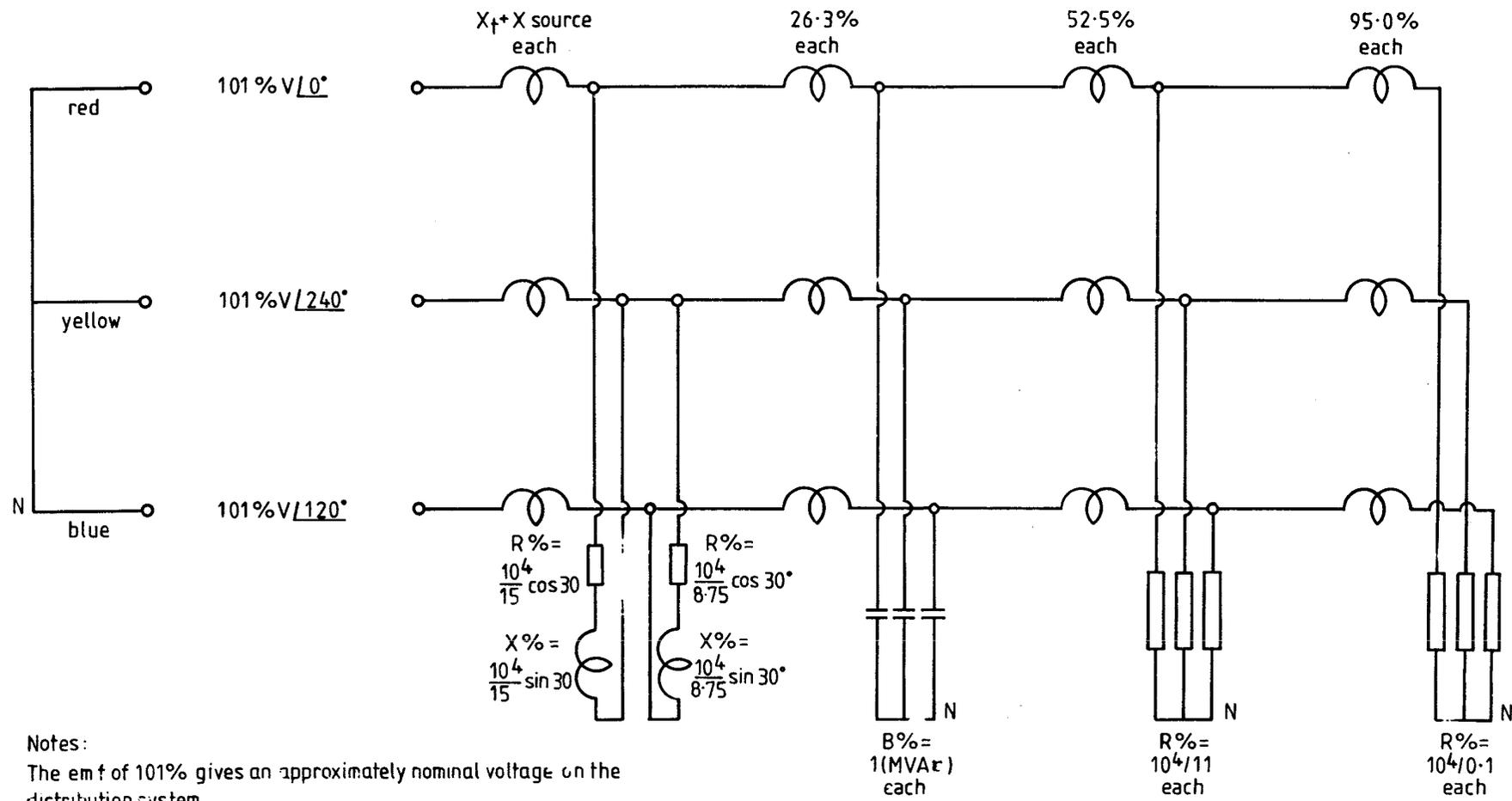
$$C = 0.1 \mu\text{F}$$



Phasing Diagrams ; vectors marked † would be given by HARP for the red phase



**FIGURE B4: EXAMPLE OF SUPPLY SYSTEM DETAILS FOR FUNDAMENTAL VOLTAGE DROP CALCULATIONS**

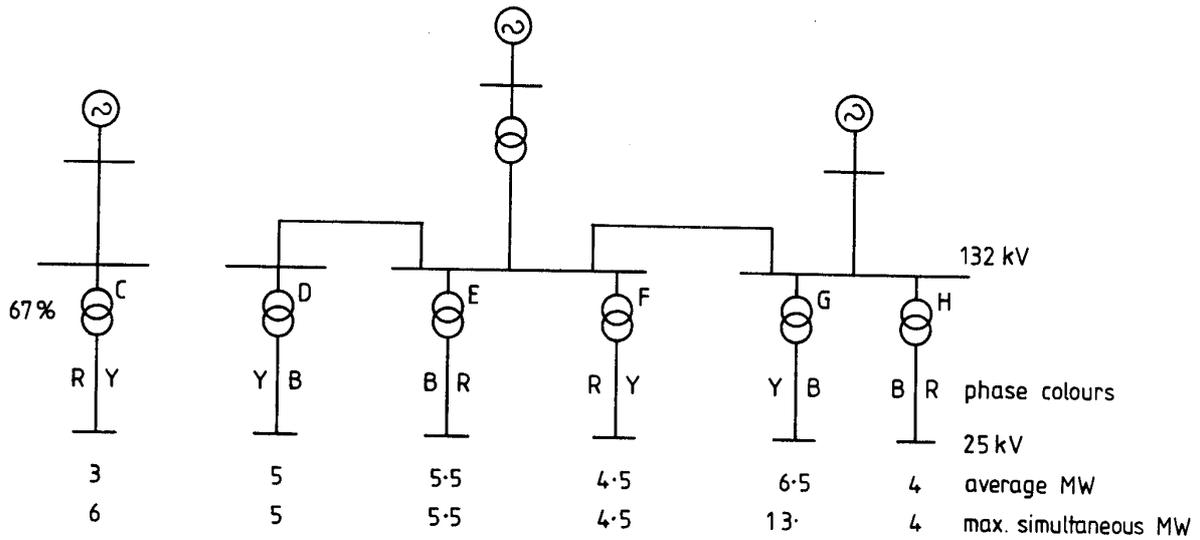


**Notes:**

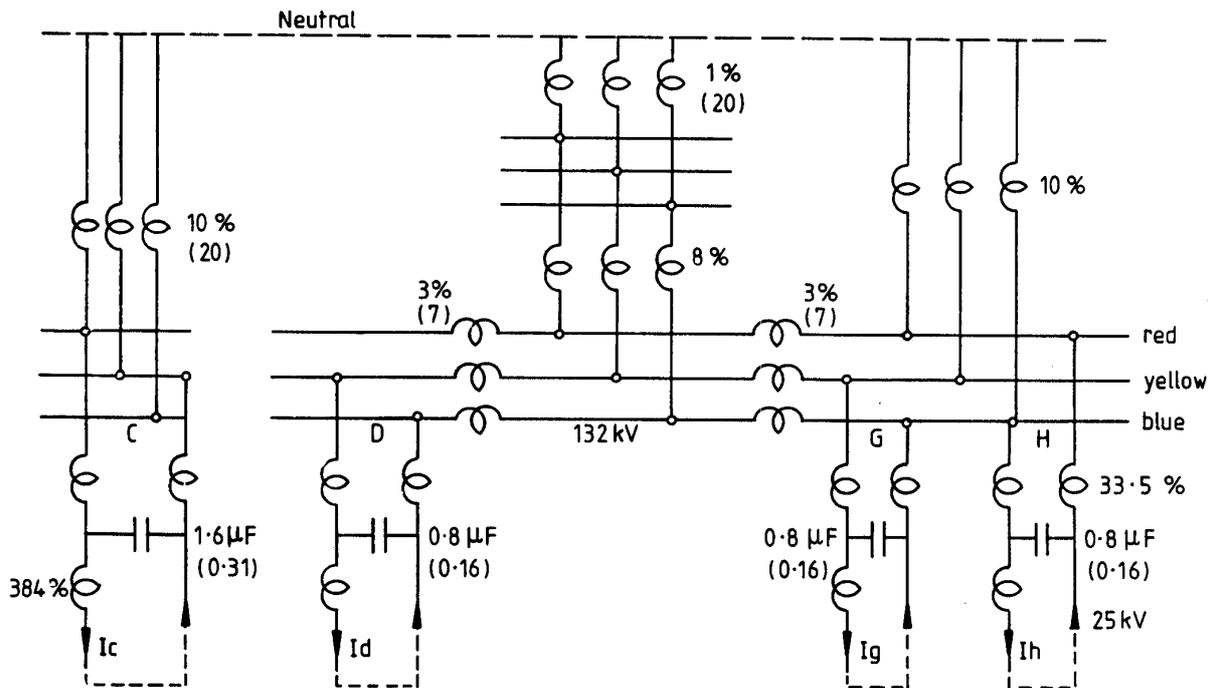
The emf of 101% gives an approximately nominal voltage on the distribution system.

The Program puts all shunt impedances and voltages to the reference bus N

**FIGURE B5: REPRESENTATION OF FIGURE B4 FOR HARP SUPPLY**



**FIGURE B6: EXAMPLE OF TRACTION SUPPLY DETAILS**



**FIGURE B7: REPRESENTATION OF FIGURE B6 FOR HARP STUDY**

Note : (Figures B6 and B7)  
 Showing system reactances in % on 100 MVA base and capacitance  
 MVar in ( ). Three-phase load circuits not shown.  
 Circuits E and F out of service.

**TABLE B1 ASSUMED LOADS IN FIGURE B6**

Feeder Stations	C	D	E	F	G	H
Second Stage Emergency MW	6	10	-	-	17	4
Displacement Angle	31	33	-	-	36	30
Displacement Factor	0.87	0.84			0.81	0.87
MVA	7	12	-	-	21	4.6
1% (1.0% = 23.09 A)	12	21	-	-	36	8
System Voltage Angle	0	0			+2	+2
Relative Displacement Angle	0	-2			-5	+1
Total Angle, A	0	-2			-3	+3

**TABLE B2 GIVEN INJECTED CURRENTS, %, IN FIGURE B7 ASSUMING AN INDUCTIVE SYSTEM**

Harmonic	Feeder Station Currents			
	Ic	Id	Ig	Ih
F	12/321	21/199	36/198	8/84
3	1.9/268	3.3/262	5.5/259	1.2/277
5	0.9/193	1.6/303	2.7/298	0.6/88
7	0.4/109	0.7/335	1.3/328	0.3/250
9	0.17/29	0.3/11	0.5/2	0.1/56
11	0.08/310	0.14/48	0.24/37	0.05/223
13	0.06/214	0.1/68	0.18/55	0.04/13

**TABLE B3 132 kV FUNDAMENTAL VOLTAGE DROPS, %, IN FIGURE B7**

Stations	C	D	G
V red	1.2/48	0.3/354	0.4/353
V yellow	1.2/228	3.2/288	2.8/288
V blue	0.	3.4/113	3.0/115
V n.p.s	0.7	1.8	1.5

**TABLE B4 132 kV HARMONIC RESULTS, %, IN FIGURE B7**

Harmonic	At Station C		At Station D		
	V red	Ic	V red	V yellow	V blue
3	0.7	1.84	0.2	1.6	1.4
5	0.9	0.86	0.2	1.5	1.6
7	2.6	0.29	0.1	1.2	1.2
9	0.3	0.19	0.1	1.0	0.9
11	0.09	0.08	0.2	1.4	1.5
13	0.05	0.06	0.1	0.9	0.8
Totals	2.8		0.4	3.2	3.2

## APPENDIX C

### PHASE BALANCING

Figure C1 shows the circuit for balancing a single-phase line-to-line connected load on a three-phase system, while Figure C2 shows the vector diagrams for the individual branch currents and their summation to effect the required symmetrical loading. It should be noted that the inductive arm is connected between the unused phase and the leading phase of the load.

The balancer will improve the power factor of the resultant three-phase load and can, depending on the component values chosen, be designed to provide complete or partial balancing. For full balancing of a single line-to-line connected load it can be shown that the resultant power factor of the three-phase load at 50 Hz will also be unity. For a load of S MVA comprising real and reactive components P and Q, the required component values for full balancing would be rated at:

$$E \dots\dots -j S \sin \theta = -j Q$$

$$F \dots\dots -j (S/\sqrt{3}) \cos \theta = -j P/\sqrt{3}$$

$$G \dots\dots +j (S/\sqrt{3}) \cos \theta = +j P/\sqrt{3}$$

In practice it may be uneconomic to provide full phase balancing and a criterion may be adopted whereby the railway load at a supply point should not contribute more than x% n.p.s. voltage. In this case the part of the maximum railway load S to be balanced would be

$$S - \frac{xF}{100}$$

where F is the minimum plant fault level at the point of common coupling. This assumes no interconnection with other supply points and a somewhat smaller compensation may be possible where a HARP study of the interconnected system indicates that some of the load is compensated by contributions from other supply points.

Where two line-line loads are connected at the same supply point, as shown in Figure C3 the nature of two arms must be interchangeable and depend on the relative values of the two loads. Provided both loads exist simultaneously it can be shown that there could be some reduction in the MVA<sub>r</sub> requirement for two of the three arms. However, since it is a planned outage condition that both supplies can be connected to the same phase pair, the reduction in the component rating cannot be realised. Where a balancer is used, it is preferable for both track sections to be fed from the same phase pair as this avoids the need to interchange inductor and capacitor.

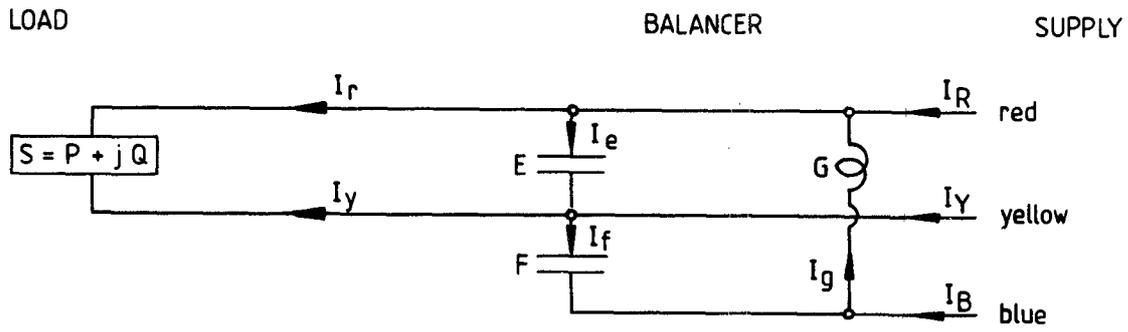


FIGURE C1: BALANCER FOR SINGLE LOAD

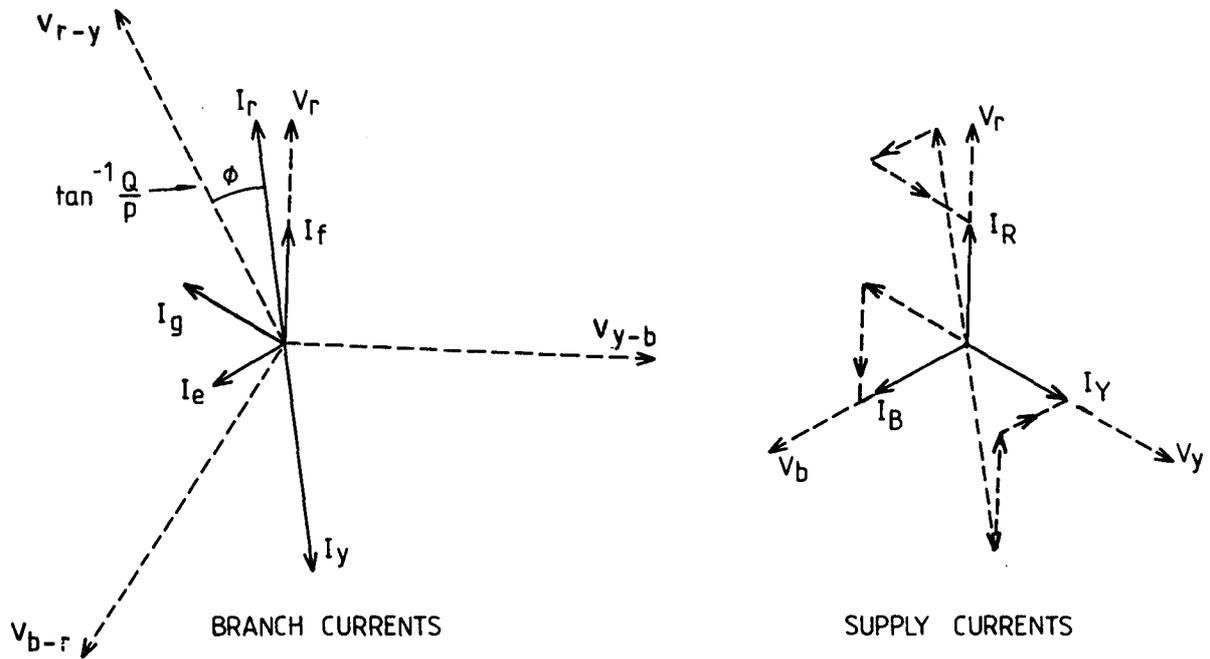


FIGURE C2: VECTOR DIAGRAMS FOR FIGURE C1

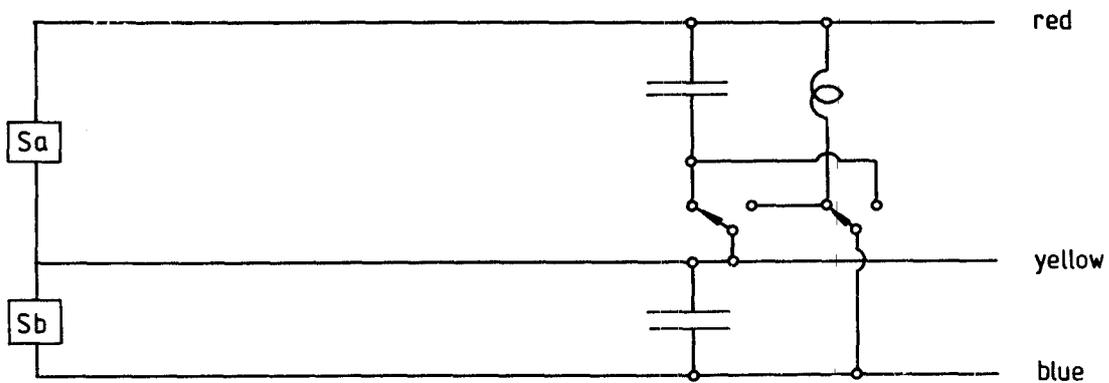


FIGURE C3: BALANCER FOR TWO LINE-TO-LINE LOADS

## APPENDIX D

### REFERENCES

<b>TITLE</b>	<b>SECTION</b>
ACE Report 73 (1979): Report on Limits for Harmonics in the UK Electrical Supply Industry	7
BRB Specification AC5 (1979): Specification for 25 kV Two-Core Concentric and Single-Core Cables, Auxiliary Cables, Accessories and Associate Cable Routes.	10.2
BRB Specification AC10/3 (1973): Specification for 25 kV and 6.25 kV Switchgear and Ancillary Equipment	10.4
Code of Practice CP 1013: 1965: Earthing	11.3.2(a)
CEGB Planning Memorandum PLM-SSB-1 (1981): Planning Procedure for 25 kV A.C. Railway Supplies	4.5 and Table 1
CEGB Specification CEGB RT (1977): Specification and Schedules for 275 kV and 132 kV Transmission Transformers for Use in Connection with Single Phase Supplies to British Railways Electrification Projects	10.1
CERL Overhead Line Ratings Ref. RD/L/N129/79: A Statistical Approach to the Thermal Rating of Zebra Conductors Based on Real Weather Observations	10.3.2
EEB Specification EEB/25/DC (1980): Standard Design for 25 kV Single Phase Double Circuit Overhead Line	10.3
EEB Specification No. 305 (1981): 1981 Specification for Single-Core Concentric Earth Return 25/44 kV Polymeric Cable and Accessories for Supply to Electrified Railways	10.2
Electricity Supply Regulations 1937	10.4.3 and 11.2
Electricity (Overhead Lines) Regulations 1970	10.4.3 and 11.4.3

Engineering Recommendation G.5/3 (1976): Limits for Harmonics in the United Kingdom Electricity Supply System	Table 2
Engineering Recommendation G.12/2 (1982): National Code of Practice on the Application of Protective Multiple Earthing to Low Voltage Networks	11.3.2(d)
Engineering Recommendation G.38 (1979): Operational Procedure Associated with Electricity Supplies for Traction Purposes on A.C. and D.C. Electrified Lines	2.1.3 and 14
Engineering Recommendation M.24 (1973): Code of Practice for the Metering of Supplies from the CEGB	10.5
Engineering Recommendation P.2/5 (1978): Security of Supply	5
Engineering Recommendation P.7/2 (1970): Supply to Arc Furnaces	Table 2
Engineering Recommendation P.8 (1965): Supply to Colliery Winders and Rolling Mills	Table 2
Engineering Recommendation P.13/1 (1979): Electric Motors: Starting Conditions	Table 2
Engineering Recommendation P. 16 (1975): E.H.V. or H.V. Supplies to Induction Furnaces	7 and Table 2
Engineering Recommendation P. 18 (1978): Complexity of 132 kV Circuits	3.2.1(b)
Engineering Recommendation S.5/1 (1966): Earthing Installations in Substations	11.3.2(b)
Factories Act 1961	11.2
Health and Safety at Work Act 1974	11.2
HARP03 Report CS/C/P300 (1980): Harmonic Impedance and Penetration Program	8.2.3 and Appendix B
HARP04 Report CISD/CC/P687 (1983): Harmonic and Unbalanced Load Program	8.2.3 and Appendix

B

SSEB Specification L21A (1971):  
25 kV Overhead Line of Unearthed Construction 10.3

SSEB TDM 13/10001 1970  
Security of Supply 3.2. 1 (b)

Transmission Plant Standard 6/19 (1982):  
Application of Metering to Tariff Circuits 10.5