NORTHERN IRELAND ELECTRICITY plc
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VOLTAGE CRITERIA DOCUMENT (PLM-ST-9 DEC 1985)

1. General Use

Document PLM-ST-9 is a guide to the planning of developments to the NIE system, each scheme for reinforcement or modification being individually assessed by NIE in the light of economic and technical factors obtaining.

2. Particular Modification in Respect of Voltage Step Changes

In carrying out outage security studies with regard to the 275kV or 110kV system the following criteria will be applied.

(a) A secured single circuit outage will not cause a step change in voltage greater than 6%.

(b) A secured double circuit outage will not cause a step change in voltage greater than 10%.

(c) The 110kV voltage at bulk supply points will not fall below 90% during conditions (a) and (b).

(d) The 110kV voltage at main super grid points shall be considered for planning purposes to not exceed 103% at any time.

Notwithstanding the above the main consideration for voltage at 33kV bulk supply points is that after any secured outage it is necessary that the 33kV voltage can be restored to 100% by use of local tap changing.

This is a variation to the Standard given in PLM-ST-9 in respect of the NIE 110kV and 33kV systems and the particular mode of operation of these systems.

Central Electricity Generating Board

Technology Planning and Research Division

System Technical Branch

VOLTAGE CRITERIA FOR THE DESIGN OF THE 400 kV AND 275 kV SUPERGRID SYSTEM

PLANNING MEMORANDUM PLM–ST–9

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CEGB In Confidence

Central Electricity Generating Board

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Voltage Criteria for the Design of the 400 kV and 275 kV Supergrid System

C O N T E N T S

2nd Impression, January 1986

1. FOREWORD

1.1 Criteria for system voltage are necessary to ensure that satisfactory conditions can be maintained on the CEGB 400 kV and 275 kV supergrid system and that acceptable voltages are available to Area Boards and CEGB auxiliary equipment. The Criteria refer to steady state conditions and do not directly encompass transient or dynamic considerations.

1.2 This system planning document forms the first issue of Planning Memorandum PLM-ST-9, and supersedes Issue 1 of TDM 13/9 (Design Memorandum 099/32) which was entitled 'Criteria for System Voltage Control and Reactive Compensation Studies'. A number of changes have been made to the format, technical content and emphasis of the memorandum. Since TDM 13/9 was released in May 1967 two particular developments have occurred; firstly, the change in interface between the CEGB and Area Boards following the transfer of ownership and responsibility for 132 kV assets, and secondly, the further changes in supergrid system operating characteristics from the original concept of approximate zonal balance of generation and load to a long-distance bulk transmission system. Among the technical changes, it may be noted that the voltage step-change limits (Criterion A) now require demand group load response to voltage change to be included in the assessment of network performance.

1.3 The Criteria stated in this memorandum are formulated to meet the following requirements:

(i) To keep system voltages within a bandwidth of levels which at the upper limits ensure that equipment is not overstressed, and at the lower limits provide satisfactory system performance and acceptable voltage to Area Boards and CEGB auxiliary equipment, under normal and secured outage conditions.

(ii) To limit the step change of voltage following switching, fault clearance, or other changes in system conditions planned for at the design stage.

(iii) To ensure that adequate provision is made at the system planning stage for reactive power reserves such that system voltage behaviour is acceptable over the range of operating conditions with due regard for voltage stability.

1.4 The Criteria are presented in tabular format in Section 4 and supplementary technical information is given in Section 5. Advice on estimation and application of load response characteristics in voltage studies is contained in Appendix 1.

2. SCOPE

2.1 This memorandum specifies steady-state voltage limits for the 400 kV and 275 kV supergrid system and associated points of connection for Area Board networks in England and Wales. The Criteria are intended for use in network analysis at the system planning stage to ensure that sufficient margins are provided for satisfactory operation under all demand conditions in practice.

2.2 The general principles set down in the Criteria are also applicable to the voltage supplied to CEGB Direct Consumers. These are special cases which may warrant individual consideration. For a.c. traction supplies to British Rail, more specific information will be found in Reference 7.5.

2.3 The Criteria are applicable throughout the load cycle but have been prepared within the framework of the CEGB Transmission System Planning Standard (Reference 7.2) and, as such, are generally formulated for examination of peak demand conditions with the network initially intact and then, if appropriate, subject to secured outage, i.e. fault tripping, conditions. An exception to this general statement is Criterion C, referring to high system voltages, which is usually most applicable to minimum demand conditions.

2.4 In the majority of cases, however, a system designed to these criteria will result in a network with sufficient capability to meet off-peak requirements and maintenance outages. Where necessary, off-peak problems should be studied individually and the voltage limits stated in the Criteria applied to ensure adequate voltage performance for the planned running arrangements and specified circuit trippings.

2.5 Where off-peak studies identify unsatisfactory voltage performance, the out of merit operation of generating plant should be evaluated as an alternative to installing reactive compensation plant or other measures.

2.6 The Criteria defined in this document make some allowance for uncertainties in long term forecasting of demands, power factors and other data. Where more accurate information is available, provision is made for a relaxation of the Criteria in certain cases.

3. DEFINITIONS

The following terms are used in this document and are defined as follows:

Circuit: The part of a network between two or more circuit breakers including transformers, cables, overhead lines, etc. For the purpose of this document, a generator outage is treated as a circuit outage, as also is the outage of a single section of busbar.

Corrective Action: Manual and automatic action taken after an outage or switching action to assist recovery of satisfactory voltage conditions; for example, tapchanging or switching of plant. Figure 1 indicates the typical timescales.

Interconnected:	A network operating configuration in which a substation or group of substations receives electrical supply from two or more independent sources.
Normal:	When used to describe a network, refers to the planned network with all circuits in service in the area of interest.
Phase 1, 2, 3 & 4:	Time periods following fault clearance or switching action which are defined for reference as shown in Figure 1.
Secured Outage:	A single circuit, two circuit or double circuit outage for which the remaining supergrid and/or Area Board network is designed to remain intact without unacceptably high or low voltages, or thermal overloading.
Supergrid Network:	The 400 kV and 275 kV power system including supergrid transformers and generators connected at these voltages.
Sustained Condition:	The network voltage profile attained following a Secured Outage and all available corrective action.

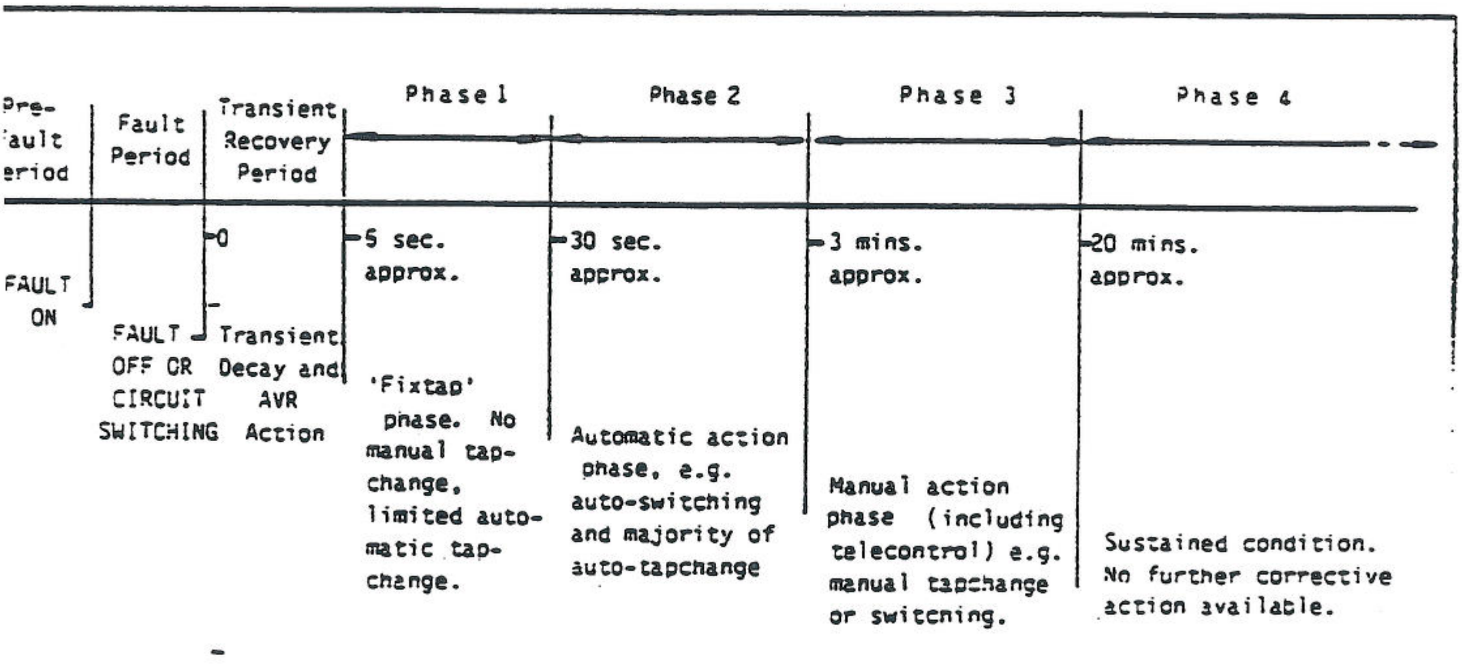


FIGURE 1: DEFINITION OF POST-OUTAGE TIME PHASES

4. VOLTAGE CRITERIA FOR SYSTEM DESIGN

4.1 INTRODUCTION

The Criteria are presented in four separate Tables as follows:

CRITERION A: Voltage step changes

CRITERION B: Lowest sustained supergrid voltages

CRITERION C: Highest system voltages

CRITERION D: Voltages supplied to Area Boards and CEGB Auxiliaries

Within each table the limiting voltage conditions or other considerations are stated as Constraints I, II, etc., and explanatory information is given in the adjacent Remarks column. Cross-references are made to Section 5 which provides supplementary information for users seeking supporting details and application notes.

4.2 APPLICATION

The Criteria are applicable at the system planning stage to those secured outage conditions that are required to be considered under the CEGB Transmission Planning Standard (Reference 7.2) and Electricity Council Security of Supply Standards (Reference 7.3). As a general principle it is not intended that application of the Criteria should warrant system capital investment or other measures to meet an operational outage condition that is outside Security Planning Standards. The exceptions to this general statement are as follows:

(a) With regard to voltage rise conditions only, Criterion C refers, the outage(s) due to a fault on any circuit breaker, including a bus coupler or bus section switch, should also be considered.

(b) In the application of all criteria, consideration of single circuit outages (but not double or two circuit cases) should be extended to include single busbar sections.

4.3 For overhead lines, two circuit and double circuit outages should in the first instance be examined as both simultaneous and overlapping events and the criteria applied in each case. Any unacceptable simultaneous two circuit overhead line outages should be identified but compliance with the criteria for this onerous condition may be waived following detailed examination of local conditions. (Reference in Operation Memorandum No.3 to Designated Single Circuit Pairs should be noted). In the case of two cable circuits, overlapping events only should be considered, unless it is judged that local circumstances create an abnormally high liklihood of simultaneous fault outages.

4.4 Criterion A, voltage step changes, also applies to normal operational switching (e.g. switching for voltage control purposes) subject to the constraints stated in the table, and should be applied to each stage of an operational switching sequence in turn.

4.5 — Voltages in excess of those specified in Criterion C column (b), for highest system voltages, should on no account be sustained on the system. Criteria A, B and D are intended as guides to good practice and it is only permissible to depart from them if a detailed assessment justifies it on technical, reliability, economic and, where applicable, fuel policy considerations. Departure from the Criteria may specifically be justified in the cases where the Constraints are necessarily generalised, and these are indicated in the relevant tables. Where appropriate, any variation must be jointly assessed with the Area Board.

4.6 For application of these criteria, network analysis should normally be undertaken using an a.c. power flow program (e.g. OPFLØ2), incorporating, where appropriate, the load response characteristics, automatic tap changing and other features as applicable to the Phase 1, 2, 3 and 4 timescales.

4.7 THE CRITERIA

The Criteria are presented in tabular form overleaf.

CRITERION A: Voltage Step Changes

CONDITION	EFFECT	CONSTRAINTS	REMARKS
Secured Outage(s) on the 400 kV or 275 kV supergrid network.	Voltage rise or fall at the point of supply to Area Boards (typically the SGT lower voltage side).	I The voltage change from the steady-state, pre-fault condition should not exceed +6% or -6%. II For the case of a secured outage which includes the loss of supergrid transformers, the voltage change should not exceed +6% or -12%.	1. Criterion A is applicable to the change in voltage between that of the pre-fault period and that of Phase 1, under all demand conditions. 2. Load response characteristics are to be taken into consideration (see 5.8). 3. Consumers may be subjected to two disturbances, first a voltage fall due to the fault outage and then a rise when healthy equipment is returned to service. 4. Automatic tapchange action (mainly in Phase 2) will return the voltage responsive demand and may decrease system voltages further. Voltage stability should be examined in detail if supergrid voltages fall below the values stated in Criterion B (see 5.19). 5. Constraint I is applicable to the loss of a supergrid transformer in a tap-stagger arrangement. 6. Constraint II does not apply to the loss of 400/275 kV transformers. 7. Constraint III assumes that the switching operation will not be repeated at less than 2 hourly intervals. If more frequent than 2 hours a limit of 1% should be applied. These limits are to prevent annoyance to consumers and are related to Engineering Recommendation P13/1. Examination of individual cases may permit some relaxation. See Reference 7.9. 8. The step change should not exceed +/- 6% where generating station auxiliary supplies are derived from the Area Board network. 9. The 6% and 12% voltage step change limits are a measure of system performance in the immediate post-fault condition. They do not refer directly to the permitted statutory variation in declared voltage.
A normal operational procedure, e.g. switching of circuits or plant for voltage control purposes.		III The voltage change from the steady-state, pre-switching condition should not exceed +3% or -3%.	

CRITERION B: Lowest Sustained Supergrid Voltages

CONDITION	EFFECT	CONSTRAINTS	REMARKS
Normal 400 kV and 275 kV networks in service, without outages.	Sustained voltage conditions on the 400 kV and 275 kV systems.	I 400 kV voltages should not be lower than 97.5% and 275 kV voltages should not be lower than 95% of nominal.	1. Constraint I applies to the normal pre-fault condition. Constraints II to V should be met at the start of Phase 4 (sustained condition) without widespread re-tapping of generator transformers to increase Mvar outputs. (See 5.25).
Secured outage(s) on the 400 kV or 275 kV supergrid network.		II Voltages less than 95% of nominal should not be sustained on any part of the 400 kV system that is operating in an inter-connected mode post-fault. III Voltages on the 400 kV system may be permitted to fall below 95% but not less than 90% where: (a) the 400 kV system is operating in a radial, not interconnected mode, post-fault and (b) not more than one supergrid substation is subjected to 400 kV voltage less than 95% and, (c) the affected supergrid substation has no lower voltage interconnection to other supergrid sub-stations Note remarks 3, 4 and 5. IV Voltages on the 275 kV system may be permitted to fall below 95% but not less than 90% (see remark 6). V A group of generation should not be required to sustain Mvar outputs beyond declared limits as a consequence of the secured outage. (See remarks 7 & 8).	2. Voltages less than 95% should not be sustained where generating station auxiliary supplies are derived from the 400 kV or 275 kV systems. 3. 90% voltage on the 400 kV or 275 kV system is only acceptable where: (a) Sub-station main and auxiliary plant is not adversely affected (see 5.13). (b) the demands and power factors used in the network studies are judged to be well defined and not subject to wide tolerances (see 5.6) 4. With reference to Constraints III and IV, voltages of 90% would be un-acceptable, even if achievable, at sub-stations where directly-connected generation is running. 5. Constraints III(b) and (c) are intended to ensure that a 90% voltage condition is localised. For two or more sub-stations which form a sub-group which post-fault is electrically remote from the main interconnected system, it may be acceptable for the whole sub-group to operate at 90% subject to examination of individual cases for voltage stability. Also, lower voltage inter-connection may be acceptable post-fault, subject to similar examination (see 5.20). 6. Voltages below 95% on 275 kV systems running in an interconnected mode should be examined carefully, with particular attention to sensitivity at the lower limit of 90%. 7. Constraint V will generally be effective in conjunction with the 95% voltage limits. 8. In the sustained condition, after acceptable generator transformer re-tapping (see 5.21), the Criterion B constraints should be met without generators exceeding declared Mvar capabilities.

CRITERION C: Highest System Voltages

NETWORK	(a) MAXIMUM OPERATING VOLTAGE - SYSTEM PLANNING STAGE	(b) EQUIPMENT RATED VOLTAGES
132 kV	139 kV (+5%)	145 kV (+9.8%)
275 kV	289 kV (+5%)	300 kV (+9.1%)
400 kV	410 kV (+2.5%)	420 kV (+5%)
	420 kV (+5%) - where the cost of achieving +2.5% is excessive and means will be available to reduce it within 15 minutes.	440 kV (+10%) - where reduction to 420 kV (+5%) is achievable within 15 minutes.

Remarks: (1) Criterion C applies to Phase 1, 2, 3 and 4.

(2) The equipment rated voltages in column (b) are shown for comparison purposes: however, at the system planning stage the column (a) figures should be complied with to allow for uncertainties in demands, generation capabilities and geographic disposition, etc. Some relaxation of the column (a) figures may be possible following consultation with interested parties.

(3) Voltage in excess of the column (b) values must not be sustained in practice owing to the risk of damage to consumer, Area Board and Generating Board equipment. Unless a high voltage condition can be rectified by immediate corrective action the Grid Control Engineer is instructed to take such action as is required to safeguard apparatus, even if this results in disconnection of supplies. (Operation Memorandum 1 refers.)

(4) The 440 kV figure in column (b) is a dispensation agreed for the 400 kV system, not a formal equipment rating.

CRITERION D: Voltages Supplied to Area Boards and CEGB Auxiliaries

CONDITION	EFFECT	CONSTRAINTS	REMARKS
Normal 400 kV and 275 kV networks in service, without outages.	Voltage at the point of supply to Area Boards (typically the SGT lower voltage side) and CEGB auxiliary supplies	I It shall be possible to achieve up to 105% of nominal voltage to the Area Board and not less than 100% to CEGB auxiliaries.	1. Criterion D specifies separate constraint for each time Phase. Constraint II should generally be met at the start of Phase 4 (sustained condition) without widespread generator transformer tapchanging to increase Mvar outputs (see 5.25). Lower sustained voltages (typically 95-100%) may be acceptable following detailed examination of Area Board and CEGB network performance.
Secured outage(s) of the 400 kV or 275 kV network, or of supergrid transformers.		II For Phase 4 it shall be possible to achieve 100% of nominal voltage to the Area Board and to CEGB auxiliaries. (See remark 1)	2. Criterion D applies to all demand conditions up to full firm sub-station loading including SGT cyclic capabilities.
Secured outage(s) of the 400 kV or 275 kV network which simultaneously cause the loss of circuits and transformers.		III For Phases 1 and 2, whilst auto-tapchange, auto-isolation and auto-restoration are in progress the voltage supplied to the Area Board and CEGB auxiliaries is permitted to fall substantially below 100%. (See remarks 4 & 5) IV For Phase 3, when all practicable automatic action has been completed, but manual action is taking place, the voltage supplied to the Area Board is permitted to remain below 100% (see remark 6).	3. It is recognised that some Area Board networks have been optimised by normally running at voltages in excess of 100% and, in some interconnected networks, control of reactive power flow requires operation at greater than 100% voltage. 4. Under Constraints II and III, CEGB auxiliary voltage may be permitted to fall below 100% if detailed assessment shows that plant performance will not be adversely affected (see 5.16). 5. With reference to Constraint III: The lowest level of voltage to be experienced by the Area Board during Phases 1 and 2 cannot be stated as an absolute figure. The overriding requirement is for the CEGB and Area Board to be satisfied that stable voltage conditions are achievable. It is anticipated that 85-90% will be acceptable for the limited duration of Phases 1 and 2, in most situations, subject to examination of sensitivities. (See 5.5). Stability should also be examined carefully if, during this period, the supergrid voltage falls below the values stated in Criterion B. 6. Constraint IV applies to the nominal 20 minute period required for manual action post-fault, and a minimum acceptable voltage cannot be generalised. It is intended that consumer and auxiliary plant should be safeguarded but that voltages less than target may occur. It is anticipated that a voltage of 90-95% at the point of supply to the Area Board will be acceptable for the duration of Phase 3, subject to consideration of local conditions (e.g. 132 kV connected consumers).

5. SUPPLEMENTARY INFORMATION

The following section is intended for users who require a more detailed understanding of the reasoning behind the Criteria. Also, general information and reminders are provided to assist application of the Criteria to practical cases.

TAPCHANGERS

5.1 For a detailed examination of voltage performance in Phases 1 and 2 it is necessary to assess the behaviour of automatic tapchangers as their action will tend to cancel load-response effects and result in more onerous network conditions. The following notes are provided for general information.

5.2 Area Board distribution network transformers (11/.415 kV, 6.6/.415 kV etc) generally have either fixed tap ratios or off-circuit selectable taps. System transformers (132/33 kV, 33/11 kV etc) usually have on-load automatic tapchangers and supergrid transformers (400/132 kV, 275/66 kV etc) are generally provided with manually operated on-load tapchangers. However, the latter are equipped at some sites with automatic control (particularly 275/66 kV) and this is likely to become more common for all supergrid transformers, particularly in passive (non-generation) groups. Exceptions to the general rule for supergrid transformers are 400/275 kV units which are presently fixed ratio. Transformers supplying railway loads (e.g. 132/25 kV, single phase) are usually fixed ratio for smaller sizes (e.g. 10-14 MVA) and off-load selectable for larger sizes (e.g. 18-26 MVA). Generator transformers are equipped with manually operated on-load tapchangers. It should be noted that, in some cases, automatic voltage control equipment on system transformers is designed to inhibit operation for voltages outside a stated bandwidth, typically -20% to +30%.

5.3 In the absence of automatic voltage control (AVC) on supergrid transformers it can generally be assumed that Area Board transformers will automatically tapchange to attempt restoration of 33 kV and 11 kV (or equivalent) voltages before the manual operation of supergrid transformer taps. Whilst most Area Board AVC's have a time delay of 30 seconds or longer, the response of a group of AVC's is subject to variation as some AVC timing mechanisms may be partly through their cycle in response to normal load variations. Also, some AVC's are fitted with an accelerating feature to initiate inverse-time characteristic or immediate tapchanging in response to a large step change in system voltage. Post outage automatic tapchanging is significant because it will generally return voltage-responsive demand and result in system conditions becoming more onerous.

NETWORK MODELLING

5.4 In studies of abnormally low voltage conditions (typically 95% and lower), regard must be given to the possibility of voltage collapse if the maximum power transfer capability of the system is exceeded. Particular caution should therefore be exercised in preparation of network models to ensure that demands, power factors, load response characteristics and generation MW and Mvar capabilities and response characteristics in the area of interest are represented using the best data available and, where data assumptions have to be made, margins are included for confidence. Equivalent circuits and approximate representations of responsive plant should be used with care, and generator transformers should be included, particularly in the area of interest. Paragraph 5.9 provides further guidance on modelling generator MW and Mvar outputs.

5.5 Sensitivity studies should be undertaken to demonstrate that compensation or other reinforcement proposals are sufficiently robust to prevent voltage collapse for reasonable variations in study data. Judgement must be made of likely variations in the magnitudes and distributions of demands and generation or other parameters. The following comments are provided for guidance:

(a) For sensitivity checks in studies using ACS demands, without Interconnection Allowance, a 5% increase in demand above ACS figures will correspond to an 80% confidence level in demand predictions. (This assumes that a Gaussian Distribution of demand, with 6% standard deviation, is appropriate to the 4-5 year planning horizon for voltage issues). Pessimistic generation assumptions should not be made if demands have been increased for sensitivity checks. In these circumstances generation should be modelled at planned output levels. Where study assumptions make the use of PLM-SP-2 Interconnection Allowance appropriate, this may be applied for sensitivity checks in place of the 5% demand increase.

(b) It is less straightforward to provide guidance for the examination of sensitivity to perturbation in generation patterns. In terms of risk, the loss of a 'further' generator in an area at the same time as a double circuit outage is a relatively unlikely event. The most likely combination of outages involving one or more circuits and 'further' generators, will generally be the condition of one 'further' generator outage plus a single circuit outage. Thus, for a sensitivity check with a 'further' generator out of service, it is recommended that the network should be examined with one rather than two circuits out of service.

(c) For sensitivity checks of low voltage conditions it is usually acceptable for the criteria to be infringed, provided that:

(i) stable voltage conditions are attained, and

(ii) the network does not become over-sensitive to variations in other data assumptions.

The remarks in 5.21 regarding generator Mvar reserves should, however, be noted.

5.6 The estimates for future demands in a network under study may be based on predictions of system load growth or, alternatively, on forecasts dominated by planned transfers from other networks. In the latter case a knowledge of the existing load characteristics should enable the future condition to be modelled confidently. For relatively short term studies (say 5 or 6 years hence) of groups not subject to load transfers, special development or major new loads, it should also be adequate to base study demands on CM1 data interpreted where appropriate for off-peak conditions, diversity and load duration curve characteristics. In general, network loading conditions based on diversified CM1 demands should form the basis of justification when assessing the capacitive reactive compensation plant requirements of local groups, subject to sensitivity checks.

5.7 Care should be exercised in applying peak demand power factors to low voltage off-peak studies as investigations show that in certain areas the power factor may be reduced (proportionately greater lagging Mvar demand) under off-peak conditions. In the absence of better off-peak power factor data, it is recommended that demand group reactive loads (QL) in the area of interest are maintained at the values determined for peak demand conditions. This is only appropriate to demands represented at the Bulk Supply Points.

LOAD RESPONSE CHARACTERISTICS

5.8 Voltage profiles, in Period 1 particularly, will be sensitive to the load response characteristics modelled in the study. System tests have been undertaken at a number of substations to measure the response characteristic but, even where these are available, it is not always practicable to model each characteristic individually in a study. Use of measured characteristics has the further limitation that they may not be fully applicable under different seasonal or time of day conditions and, over a period of time, the load composition of a demand group may change. Appendix 1 describes a technique for predicting load response characteristics for use in voltage studies and may be applied on a generalised basis (e.g. study zones) with a suitable margin for use at the planning stage. Curves P1 and Q1 from the Appendix are recommended for general application, particularly in preliminary studies, as they represent a minimum response which tests to date indicate will be exceeded in practice. Further information on the background to the Appendix is available, see Reference 7.6.

GENERATION CAPABILITIES

5.9 For a consistent approach to generator MW and Mvar capability representation in a.c. power flow studies, the following guidelines should be observed. Application advice for the two alternative representations is described in 5.12.

5.10 REPRESENTATION (A)

Generator non-availability should be represented by discrete generator units out of service to give a whole system MW output equivalent to that calculated using the seasonal availability factors applicable to the various classes of plant. The location of units out of service should have regard to the critical circuit trippings such that worst-case conditions are represented. Non-availability should broadly be apportioned to the sending-end and receiving-end networks (where identifiable) in the ratio of the MW capacity of the generation assumed on-bars in these two networks. Mvar capability limits for the turbo-generators assumed running in the studies should be reduced from the OR1 declared values to allow for random shortfall effects. In the absence of better data, 90% capability is recommended for study purposes. However, where Mvar capability is found to be critical to system voltage performance, sensitivity to the generalised 90% should be examined and, where possible, the accuracy of the figure confirmed for the machines in question.

5.11 REPRESENTATION (B)

Generator MW outputs and Mvar capabilities should be calculated by applying the appropriate (MW) availability factor for the station directly to the declared MW and Mvar capabilities stated in the OR1 returns. Allowance for Mvar shortfall should be covered by ensuring that a satisfactory overall system Mvar reserve is retained under all secured outage conditions. A reserve in the order of 10% will usually be adequate.

5.12 APPLICATION

(i) Representation (A) is recommended for detailed examination of network problems, particularly where critical circuit trippings have been clearly identified and where the uncertainties associated with the network (e.g, generation or transmission system changes) are minimal.

(ii) Representation (B) is recommended for preliminary investigations, where critical trippings may not have been identified and where other uncertainties exist owing to the unknown longer term conditions. (B) will also be suitable for examination of whole-system problems which are expected to occur with an intact main interconnected network, due to generator or reactive compensation plant non-availability/tripping.

(iii) For the detailed examination of localised problems it is acceptable to apply (A) to the area of interest and (B) to the remainder of the network remote from the critical trippings. In some cases it will not be possible to represent average availability with discrete generator units out of service, owing to the limited number of sets in the area of interest. Where this applies, the number of sets out of service should be chosen to give a MW output for the area not greater than that calculated using the appropriate average availability factors.

(iv) The approach of Representation (A) will require careful application for areas where single large generation units make a significant contribution to that area. Where examining circuit trippings with the onerous assumption of nil output from the station, the network can be considered acceptable if stable voltage conditions are achieved even though the criteria may be infringed.

(v) With either representation, OM1 estimates of demand power factor should be used. Uncertainties in this data resulting from the planning lead time are considered to be covered by the scaled-down Mvar capabilities and the margins incorporated in the criteria voltage limits.

(vi) Reactive compensation plant should generally be represented at full nameplate Mvar capability, but where a single item of plant critically influences network performance the principles adopted for the representation of large single generation units should be applied.

AUXILIARY SUPPLIES

5.13 The integrity of auxiliary supplies is fundamental to secure electrical operation of the power system, particularly under adverse conditions. Auxiliary supplies to nuclear generating plant require the additional consideration of station safety aspects and this may form an overriding requirement when determining minimum acceptable system voltages.

5.14 Generating station and substation auxiliary supplies are derived from station transformers, unit transformers, auxiliary transformers, tertiary windings and/or Area Board networks. In many cases diesel or gas turbine-driven alternators are available in a standby mode. Station transformers are provided with on-load tapchangers and the auxiliary transformers associated with supergrid transformer tertiary windings have automatic voltage regulators if shunt reactors are connected. (Reference 7.7 refers).

5.15 For low sustained supergrid voltage conditions of 95% (Criterion B Constraint II) it will be possible to maintain 100% auxiliary voltage following tapchanger operation. In the onerous case of auxiliary supplies being derived from a remote 132 kV system having two supergrid transformers, one of which is out of service at peak demand, it is estimated that the auxiliary voltage may fall to 96-97%. In practical terms, auxiliary voltages down 95% will be acceptable. When considering likely variations to be expected in auxiliary voltages it may be noted that the automatic regulator, associated with supplies derived from certain supergrid transformer tertiary windings, is only specified (Reference 7.7) to control the 415 V supply within a bandwidth of +5% -5% and Area Board supplies are subject to +6% -6% statutorily permitted variation about the declared voltage.

5.16 For a sustained supergrid voltage of 90% (Criterion B, Constraints III and IV) it is important that adequate substation auxiliary supplies can be maintained. In particular, the behaviour of motor loads for starting and post fault re-acceleration must not be jeopardised and satisfactory performance must be confirmed before the 90% condition be accepted.

The following checklist itemises some of the substation auxiliary plant that should be considered when appraising system low voltage conditions:

(a) Unlatched contactors (drop-off voltage will be 80% or less, BS5424 refers

(b) Motor loads: air compressors, hydraulic compressors, motorised isolators, tapchanger mechanisms, cooler pumps and fans, oil plant, etc.

(c) Air dryers, Drycol breathers

(d) Cranes and hoists

(e) Heating and lighting installations

(f) Battery chargers

(g) Control and instrumentation computers.

It should be noted that high pressure discharge lamps may extinguish at 80% voltage (approximately) and may not restrike for several minutes, until cooled. Panel metering, including frequency meters, will generally operate satisfactorily down to 50% voltage and tariff metering will remain within 0.5% accuracy down to 90% voltage (BS5685 Class 0.5). Automatic synch-check relays of DAR equipment will generally be inhibited whilst voltages remain below 85% and the possibility of DAR failure should be examined if sustained low voltage conditions are predicted.

5.17 The possibility of utilising site standby generators to alleviate low substation auxiliary voltages should be examined. Automatic starting for conditions of low voltage, rather than no voltage, may be necessary.

MAIN PLANT

5.18 The secondary current cyclic capability of main transformers may be reduced under sustained low primary voltage conditions. This is due to the additional primary winding heat input to the transformer, arising from the greater primary current when the transformer is re-tapped to compensate for the low primary voltage condition. Detailed studies are required to determine individual limitations but, as an example, a supergrid double wound transformer having a 130% capability for 100% primary voltage, may typically be reduced to 120% capability for 90% sustained primary voltage, at 0.98 power factor.

VOLTAGE STABILITY

5.19 The relationship between power transferred across a system impedance and the receiving-end voltage for assumed constant MW and Mvar demands follows a simple parabolic shape, and a family of curves can be drawn for a range of sending-end voltages and receiving-end power factors. The curve becomes steeper as the knee-point is approached and, for a relatively small increase in power demand at the receiving-end, the voltage can collapse to a low level rather than continue to decline in a controlled manner. In practice, a system having generation close to the affected area may not suffer voltage collapse immediately as some machines may generate lagging Mvar beyond their continuous operating limit (see 5.23); however, individual station operators would act to manually reduce Mvar outputs to acceptable levels to prevent machine overheating or other damage (see 5.21). Also, in practice, MW and Mvar demands are not constant and the overall system effect would be a decline in system voltage, constrained by the characteristic of resistive load and under-voltage tripping of motor load, but in the extreme case causing voltage collapse, loss of generation, system splitting and partial or total cascade failure. The severity of voltage collapse, from a system point of view, will depend on the disposition of generation and fast-acting compensation, and the position of the critical fault outage in the network. It may be noted that if the maximum power transfer capability of the system is exceeded, there is a possibility of dynamic instability occurring in the form of reactive or active power oscillations. This is, however, beyond the scope of this document and requires separate analysis.

5.20 It may be noted that, for the supergrid system, significant Mvar generation is provided by circuit susceptance. However, this Mvar support is proportional to the square of the voltage and is reduced considerably under low voltage conditions and can be a significant factor in supergrid voltage collapse. The 95% constraint in Criterion B is partly determined by this consideration. For overhead lines, the net Mvar generation/deficit to the system is a function of line loading and the Natural Load of the line. In Criteria A and D, the acceptance of lower Area Board voltages under supergrid transformer outage conditions takes account of this; high circuit loading/low voltage being generally restricted to the lower voltage circuits and transformers without detriment to supergrid system net Mvar generation.

GENERATOR TRANSFORMER TAPPING

5.21 The 95% constraint in Criterion B includes a margin for variation in system demands, generator Mvar availability and other data uncertainties. This limit, and the step-change limits in Criterion A, should in most cases result in generation retaining lagging Mvar reserves. However, as described in 5.19, extreme system conditions may cause machines to generate lagging Mvars beyond their continuous operating limits. If the excess reactive generation is beyond declared capabilities, reduction in Mvar output by generator transformer tapchanging may be attempted by manual operator action. This action is likely to be ineffective if a group of generation, rather than a single set or station, is affected. Excess Mvar outputs should be examined at the planning stage (by attention to machine terminal voltages or by delimiting generator Mvar capabilities in the study) to ensure that a group of machines will not be required to sustain Mvar generation unacceptably beyond machine limits as a consequence of a secured outage. For such conditions, reactive compensation or other remedial measures may be justified, even though the voltage limits of Criterion B are not infringed. Individual cases should be assessed on their merits following consultation with interested parties.

5.22 It should be noted that in the practical situation it may be possible to alleviate excess generator Mvar output by action to reduce system MW transfers.

5.23 In general, 'Var limiters' where provided on a machine only constrain Mvar absorption, not Mvar generation. However, some newer AVR's on large machines have facilities which are set to constrain both absorption and generation.

5.24 At the system planning stage, the selection of generator transformer taps to control system voltage profiles and Mvar allocations should be fully examined. However, as this is a manual operation, variation of tap position should generally be considered only in the pre-fault period or as a longer term action assumed to take place in the sustained condition, Phase 4. This applies to alteration of taps for either increasing or decreasing generator reactive outputs.

5.25 The supergrid low voltage limits of Criterion B should generally be achievable at the start of Phase 4 without widespread re-tapping of generator transformers to increase Mvar outputs but limited re-tapping, at a single station or a group of stations, is considered acceptable.

6. RECOMMENDATIONS

6.1 It is recommended that the criteria stated in this memorandum should be used in future system design and reactive compensation studies.

6.2 The criteria should be reviewed if future generation planting causes the supergrid normal operating mode to revert to approximate zonal balance or if there is a significant increase in automatically controlled compensation plant, particularly in heavily importing zones.

6.3 The criteria have been derived within the framework of CEGB Planning Standard PLM-SP-2 Issue 1 and Electricity Council Recommendation P2/5. A review of these standards would necessitate a consequent review of the voltage criteria, particularly if a whole-year reliability analysis approach were to be adopted.

Issued by : System Technical Branch

Approved by : William Farmey Date : 12/12/85

7. REFERENCES

The following supporting documents are listed for information and, where appropriate, are cross-referenced in the main text and tables.

7.1 Planning Memorandum PLM-SP-1 Issue 1 September 1975
Planning Standard of Security for the Connection of Generating Stations to the System.

7.2 Planning Memorandum PLM-SP-2 Issue 1 January 1976
Planning Standards of Security for the Supergrid Transmission Network.

7.3 Engineering Recommendation P2/5 October 1978
Security of Supply

7.4 Operation Memorandum No. 1
CEGB Grid System Operating Procedure

7.5 Engineering Recommendation P24
AC Traction Supplies to British Rail

7.6 Report TPRD/ST/0006/R
Prediction of Demand Group Load Response Characteristics for use in Power System Voltage Studies.

7.7 Transmission Plant Standard TPS 3/13
415V Auxiliary Supplies for Transmission Substations.

7.8 Operation Memorandum No.3
Operational Standards of Security of Supply.

7.9 Engineering Recommendation P13/1, December 1979
Electric Motors: Starting Conditions.

APPENDIX 1

APPLICATION OF LOAD RESPONSE CHARACTERISTICS FOR VOLTAGE STUDIES

A1 INTRODUCTION

Load response measurements have been carried out at a number of substations (approximately 30 sites to date) for a range of system demand conditions. The tests confirm that both MW and Mvar demands are voltage responsive: in general terms, a fall in system voltage results in a fall in MW demand and Mvar demand. The Mvar response is generally greater than the MW response, which is significant in studies of system voltage as such studies are particularly sensitive to reactive power flows. An increase in system voltage similarly results in increased MW and Mvar demands, the Mvar change again being the more responsive.

The foregoing general statements hold true for any demand group where the net demand power factor is dominated by the Mvar requirements of the system loads and not circuit shunt susceptance or, where applicable, capacitor banks. Exceptions to the general rules, therefore, tend to be responses measured at supergrid substation LV busbars where the LV (132 kV) network contains considerable lengths of underground cable having a high shunt susceptance. Allowance must be made for this when applying measured or estimated characteristics for load response in voltage studies. The following paragraphs describe the methods of application for both supergrid LV busbars and bulk supply point busbars. Report TPRD/ST/0006/R describes the supporting work for this Appendix and summarises the load response measurements to date.

A2 REPRESENTATION OF LOAD RESPONSE CHARACTERISTICS

Load response characteristics can be represented in the form of polynomial equations as follows:

(a) For MW Response to Voltage (P/V):

$P = Po\ (A1V^{N1} + A2V^{N2})$, where

P = MW demand at voltage Vpu

Po = nominal MW demand

A1 = proportion of static load (pu)

A2 = proportion of motor load (pu)

(A1 + A2 = 1.0)

N1 = 2 N2 = Zero

(b) For Mvar Response to Voltage (Q/V):

$Q = Qo\ (B1V^{M1} + B2V^{M2} + B3V^{M3})$, where

Q = Mvar demand at voltage Vpu

Qo = nominal Mvar demand

B1 = proportion of reactive static load (pu)

B2 = proportion of Fe saturation reactive load (pu)

B3 = proportion of reactive motor load (pu)

M1 = 2 M2 = 7 M3 = -2

(B1 + B2 + B3 = 1.0)

The coefficients A1, A2, B1, B2, B3 will vary between load groups and are entered as required in the a.c. load flow program OPFLØ2.

A3 APPLICATION OF MEASURED LOAD RESPONSE CHARACTERISTICS

Details of measured load responses are provided in separate CEGB technical reports which include appropriate A1, A2 and B1, B2, B3 coefficients for use in the OPFLO1 program representation. Caution is required in applying these responses and the following points should be noted:

I The measured response characteristics are only directly applicable for the particular measurement busbar and for the demand and power factor at the time of test. For example, the Q/V characteristic measured at a supergrid LV busbar should not be applied to loads represented in a study at the Bulk Supply Point busbars unless it is ascertained that 132 kV network susceptance does not have a predominant effect. Particular care should be taken if the test measurements refer to a net leading power factor group. The polynominal coefficients derived for a leading Mvar demand will result in an invalid representation if applied to a lagging Mvar demand in the study model (the response characteristic is likely to have the wrong sense and will increase the lagging Mvar demand for reducing voltage).

II If the characteristic was measured at a different demand level or net power factor, or if it is required to eliminate the effects of 132 kV susceptance from the characteristic, then the characteristic should be modified as described in report PL-ST/10/78 (S.W. Peninsula load response tests) Appendix II.

III Some measured responses have a very marked Q/V drop-off which, in extreme cases, changes the demand power factor from lagging to leading. In voltage studies, particularly of peak demand low voltage conditions, a more cautious characteristic is recommended to provide a study margin unless it is ascertained that the measured response is fully applicable for the demand condition and event duration being examined.

IV The measured characteristic represents a total demand group response, including the effects of circuit susceptances and, where applicable, shunt capacitor banks. The study model must therefore include the Mvar requirements of the shunt elements in the busbar Q load term and should not have system susceptances or capacitor banks entered as separate busbar shunt items.

A4 ESTIMATION OF LOAD RESPONSE CHARACTERISTICS

GENERAL REMARKS:

Analysis of measured P/V and Q/V responses shows that a valid first approximation can be made if the demand power factor and load type (e.g. industrial, domestic, etc.) are known. The estimated response characteristics are presented such that a more cautious characteristic can be selected if required and a minimum response is indicated for application where load type or power factor is uncertain. It is not intended that the estimation technique should be applied to unusual loads (e.g. experimental facilities); in such cases a measured response should be obtained if necessary. In the absence of measured characteristics, fixed MW and Mvar demands should be assumed for unusual loads.

LOAD TYPES:

The reference to load type provides an estimation of the proportion of motor load to passive load in the demand group and, in the absence of better data, can be regarded as a constant proportion, independent of demand. The load types and corresponding assumed proportions of motor load are defined as follows:

DOMESTIC LOAD:	10% Motor Demand	LIGHT INDUSTRIAL:	50% Motor Demand
COMMERCIAL LOAD:	30% Motor Demand	HEAVY INDUSTRIAL:	70% Motor Demand

A5 ESTIMATION OF P/V CHARACTERISTIC

The power/voltage characteristic for the four load type classifications are shown in Figure PV1.

The selected characteristic may be applied either at the Bulk Supply Point busbar or the supergrid LV busbar as it can be considered unaffected by the intervening (132 kV) network. If the load type differs between Bulk Supply Points an average value of % motor load should be determined, weighted by Supply Point MW demands as follows:

$$\text{Supergrid group average \% motor load} = \frac{\sum_{\text{BSP's}} (\text{\% motor load}) \times (\text{MW demand})}{\sum_{\text{BSP's}} (\text{MW demand})}$$

Study voltage profiles are not generally sensitive to P/V response and, for this application, an accurate assessment of % motor demand is not essential. It can be seen from the Figure that, at 0.9 pu voltage, a change from one load type characteristic to another only alters Ppu by approximately 5%, which is within the accuracy of measured response characteristics.

The notes on Figure PV1 should be observed.

A6 ESTIMATION OF Q/V CHARACTERISTIC

GENERAL:

The reactive power/voltage characteristics for the four load type classifications are shown in Figure QV1, sub-divided by load group (lagging) power factor.

Study voltage profiles are sensitive to Q/V response and care should be taken in applying the estimating technique, with particular regard to representation of shunt capacitive elements, as detailed below. Validation of the technique shows that the estimated Q/V response, at 0.9 pu voltage, is generally within +/-10% of the measured response and where it exceeds this tolerance it errs on the side of caution for low voltage studies by predicting a less-responsive Q/V characteristic. It may be noted that the measured results are subject to approximately +/- 5% to +/- 10% accuracy.

If an overall load type (% motor load) is required for assessing the characteristic of a group of Bulk Supply Points, the average (weighted by MW demand) should be determined using the formula in Section A5. If an overall power factor is required it should be determined from the diversified total P load and Q load of the Bulk Supply Points, excluding the Mvar contribution of circuits or, where appropriate, shunt capacitors.

I <u>LAGGING PF LOADS REPRESENTED AT BULK SUPPLY POINTS</u>

(a) Set the busbar Q load equal to the Mvar demand estimates for group load.

(b) Apply the Q/V characteristic from Figure QV1.

(c) Represent the demand group circuit susceptance, and any capacitors, as a busbar shunt. Circuit susceptance can be ignored if it does not alter the demand group power factor by more than 1%, which is generally the case for 33 kV systems and below.

II <u>LEADING PF LOADS REPRESENTED AT BULK SUPPLY POINTS</u>

A leading power factor is unusual at a Bulk Supply Point and, except for special loads which fall outside the scope of this response estimating technique, would only arise for a network having relatively long cable lengths and a low demand. In the absence of measured response characteristics it is recommended that fixed MW and fixed (leading) Mvar demands are entered in the study.

III <u>LAGGING OR LEADING PF LOADS REPRESENTED AT THE SUPERGRID LV SIDE</u>

(a) Set the busbar Q load equal to the sum of the respective Bulk Supply Point Mvar demands, diversified where appropriate.

(b) Apply the Q/V characteristic from Figure QV1, note the remarks above regarding the calculation of overall load type and power factor for a group of Bulk Supply Points.

(c) Represent the LV (132 kV) network susceptance, and any capacitor banks, as a busbar shunt.

(d) If the net power factor, including system shunt requirements, is leading or if the magnitude of the Qload term is less than twice the magnitude of the busbar shunt term, then note the comments in Section A7.

A7 FURTHER Q/V CONSIDERATIONS: GROUPS WITH LARGE SHUNT TERMS

This section applies to representation at supergrid LV busbars where either the net power factor is leading, or it is lagging but the Qshunt term is large (in magnitude: Qload < 2 x Qshunt).

It should be noted that the Mvar contribution from shunt elements represented at the busbar will be reduced in proportion to voltage squared as busbar voltage falls, and the Mvar demand term Qload will be reduced by the value of Qpu, the load response polynomial expression. The relative magnitudes of Qshunt and Qload may result in the net Mvar demand changing from lagging to leading, or a leading power factor group becoming more leading, as voltage falls. Neither of these effects may be desirable in a low voltage study if it is preferred that the results should err on the side of caution, notwithstanding that measured characteristics may confirm that these effects could occur under some conditions in practice.

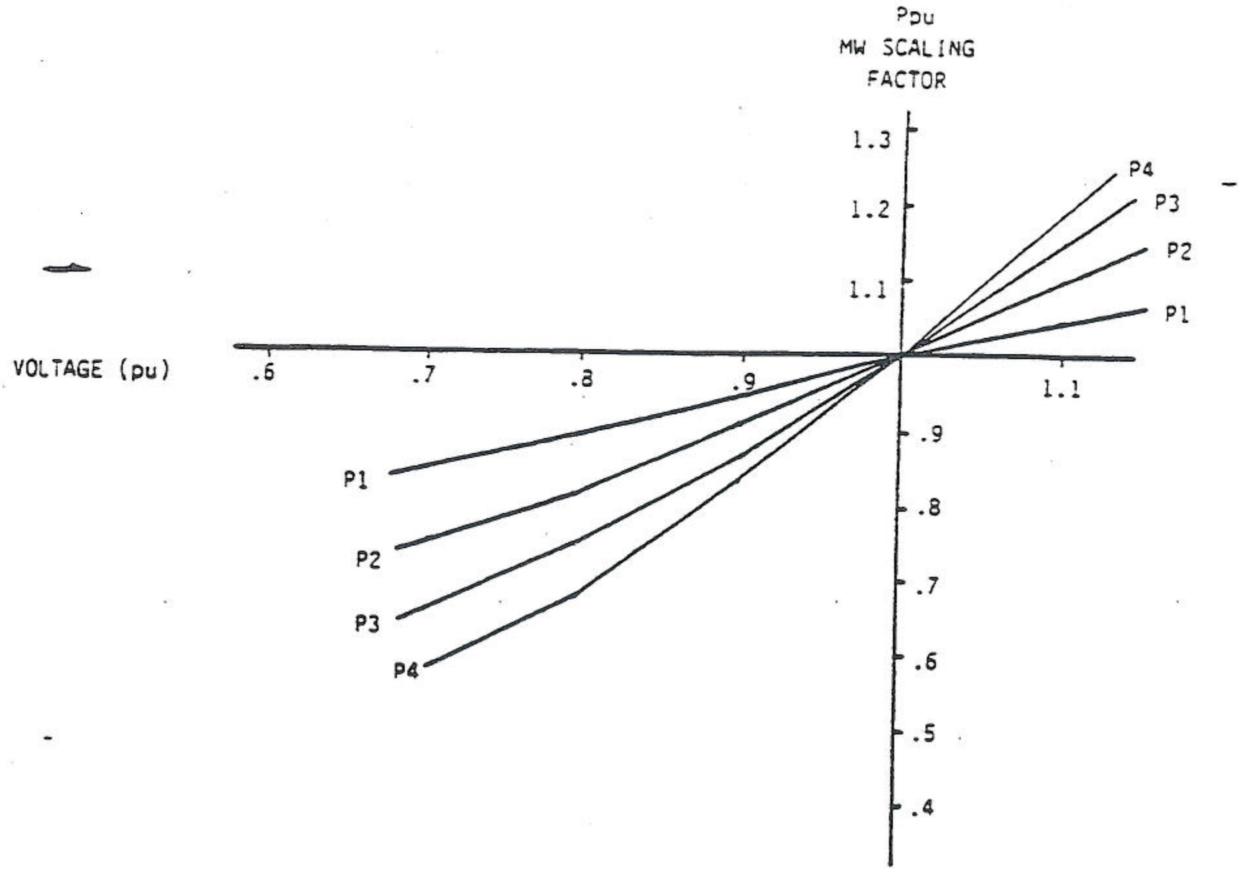
Curve Q1, the least responsive characteristic, is close to a voltage-squared response and should be applied where in doubt, as the Qshunt and Qload terms will remain broadly in proportion over the voltage range and will prevent the power factor changing significantly from lag to lead or a net leading power factor group becoming significantly more leading.

Curves Q2 to Q12 may be applied but it is recommended that the terms (-Qshunt x V pu) and (+Qload x Qpu), where Qpu is the value of the load response polynomial at V = Vpu, be evaluated to determine the acceptability of any net power factor change from lag to lead or increased leading Mvar contribution. The Qpu term can be read directly from Figure QV1 if required.

NOTE:

If, in magnitude, Qload > 2 x Qshunt the application of even the most responsive curve (Q12) at V = 0.9 pu will not cause the Mvar demand to change from (+) lag to (-) lead and the reservations expressed in this section need not be applied. If, however, voltages below 0.9 pu are to be studied the foregoing remarks should be observed.

Ref: TPRD/ST/0006/R/JGPS



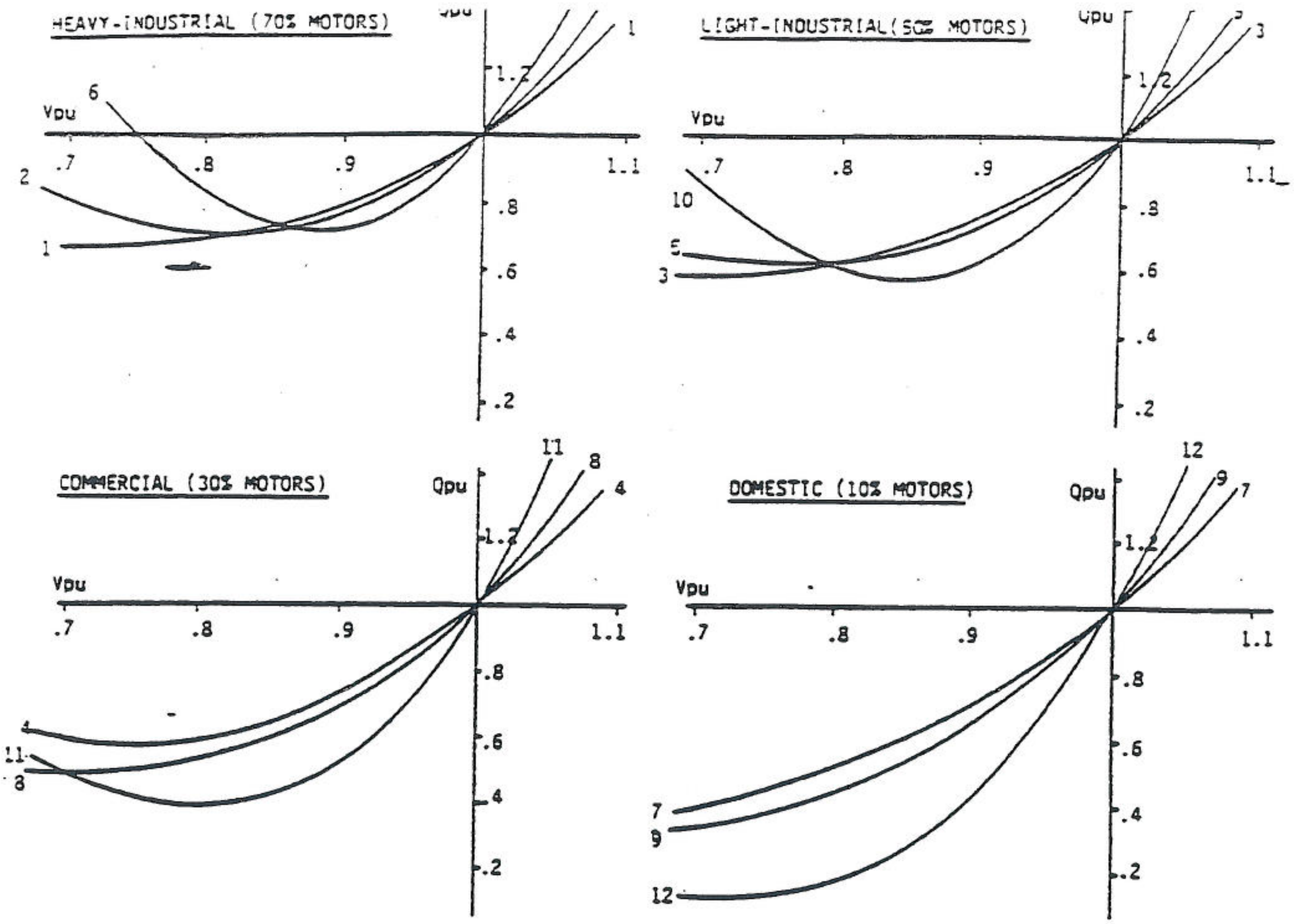
	LOAD TYPE	OPFLØ PARAMETERS					
		A1	A2	A3	N1	N2	N3
P1	HEAVY INDUSTRIAL	0.3	0.7		2.0		
P2	LIGHT INDUSTRIAL	0.5	0.5		2.0		
P3	COMMERCIAL	0.7	0.3		2.0		
P4	DOMESTIC	0.9	0.1		2.0		

NOTES: (i) Curves P1 to P4 are in order of increasing MW response to voltage change.

(ii) To give a greater study margin select a characteristic higher in the table.

(iii) If load type is uncertain use curve P1 as a minimum response for low-voltage studies.

FIGURE PV1: ESTIMATION OF POWER/VOLTAGE CHARACTERISTICS



	LOAD TYPE	LOAD PF lag	OPFLØ PARAMETERS					
			B1	B2	B3	M1	M2	M3
Q1	HEAVY INDUSTRIAL	.87	.44	.34	.22	2	7	-2
Q2	HEAVY INDUSTRIAL	.95	.07	.57	.36	2	7	-2
Q3	LIGHT INDUSTRIAL	.87	.51	.34	.15	2	7	-2
Q4	COMMERCIAL	.87	.57	.34	.09	2	7	-2
Q5	LIGHT INDUSTRIAL	.95	.18	.57	.25	2	7	-2
Q6	HEAVY INDUSTRIAL	.99	-1.16	1.33	.83	2	7	-2
Q7	DOMESTIC	.87	.53	.34	.03	2	7	-2
Q8	COMMERCIAL	.95	.28	.57	.15	2	7	-2
Q9	DOMESTIC	.95	.38	.57	.05	2	7	-2
Q10	LIGHT INDUSTRIAL	.99	-.93	1.33	.50	2	7	-2
Q11	COMMERCIAL	.99	-.69	1.33	.36	2	7	-2
Q12	DOMESTIC	.99	-.45	1.33	.12	2	7	-2

NOTES: (i) Curves Q1 to Q12 are in order of increasing Mvar response to voltage change.

(ii) To give a greater margin in low-voltage studies, select a characteristic higher in the table.

(iii) If load-type or pf is uncertain use curve Q1 as a minimum response for low-voltage studies.

(iv) "Load PF" is exclusive of system shunt capacitive elements.

FIGURE QV1: ESTIMATION OF REACTIVE POWER/VOLTAGE CHARACTERISTICS