65

AC HARMONIC FILTERS AND REACTIVE COMPENSATION FOR HVDC WITH PARTICULAR REFERENCE TO NON-CHARACTERISTIC HARMONICS

Prepared by members of Working Group 14.03
(Filtering and Reactive Compensation for HVDC) :
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SUMMARY

AC HARMONIC FILTERS AND REACTIVE COMPENSATION FOR HVDC WITH PARTICULAR REFERENCE TO NON-CHARACTERISTIC HARMONICS

By Alain Le Du, Working Group 14-03 Convener

1. INTRODUCTION

In 1979, Working Group 14-03 published a paper in issue 63 of ELECTRA, entitled "AC Harmonic Filters and Reactive Compensation for HVDC - A General Survey." This paper detailed the various problems associated with harmonic filtering and reactive power compensation for converter stations used for HVDC transmission. It also indicated which methods were used to solve these problems in the 18 links in operation or under construction at that time. For reactive power, Working Group 14-03 published a second report in 1983 on the "state-of-the-art" in compensation techniques: "Use of Static or Synchronous Compensators in HVDC Systems".

HVDC transmissions have shown a dramatic increase in applications over the last ten years, due to their specific technical and economic advantages. For example, in 1988, 68 links were identified by Working Group 4 in CIGRE Study Committee 14 (DC links): 35 links are in service and 33 are in the planning or construction stage.

For harmonics filtering, it was considered necessary to carry out a new survey based on experience with the most recent links. The present paper aims to update information published in ELECTRA issue 63. It details the methods used to solve the problems caused by low-order, non-characteristic harmonics (below 11th order). Characteristic harmonics are those generated by a presumably ideal converter. In modern installations equipped with 12-phase bridges, this applies to 11th, 13th, 23rd and 25th order harmonics on the network AC side, or $12\,k \pm 1$ order. Conversely, other emitted harmonics are known as "non-characteristic" harmonics.

2. IMPORTANCE OF NON-CHARACTERISTIC HARMONICS

This section indicates the various reasons why problems induced by non-characteristic harmonics, although not new, play an increasingly important role in a number of recently commissioned links.

- Tendency for the DC power transmitted to be high with respect to the power of AC networks which are interconnected through the DC link. The value characterizing potential problems is the short-circuit ratio, i.e. : short-circuit power / DC converted power. In some networks, short-circuit ratios in the vicinity of 3 or even less are no longer rare.

- Presence in AC networks of resonance at a low-order non-characteristic harmonics frequency. This problem occurs in networks with long overhead lines or cables. Furthermore, attenuation by the network tends to decrease as resonance frequency decreases.

- Tendency for total local compensation, in the converter station, of the reactive power absorbed by converters ($Q = 0.6\ P$, in practice). This tends to reduce the network resonance/capacitor bank frequency.

All of these factors help amplify low-order non-characteristic harmonics. In steady-state operating mode, the amplitude of non-characteristic harmonics of order 2 to 10 have, for generating factors with realistic orders of magnitude, the same order of magnitude as the amplitude of higher-order characteristic harmonics.

During a transient mode resulting from a network fault or a load rejection, transformer saturation generated by a temporary overvoltage due to reactive compensation banks also generates non-characteristic harmonics. Their impact should be taken into account to coordinate converter station insulation, especially for low short-circuit ratios.

3. GENERATION OF NON-CHARACTERISTIC HARMONICS

This section describes all parameters governing the generation of non-characteristic harmonics. All unbalances (voltage and impedance in the grid or in conversion transformers, transformation ratios between wye-delta or wye-wye connections, or delay angles when activating the 12 valves of a converter unit) play a role in generating non-characteristic harmonics. Other factors also contribute, such as DC current ripples generated by other stations in the HVDC network or by connection to an AC line close to a DC line at the fundamental frequency, as well as the presence of other harmonic disturbance sources in the AC network.

The specific influences of the various types of unbalances are studied in terms of generated harmonic orders and amplitudes. The report notably gives the results of a specific study on sensitivity of non-characteristic harmonics generation to the amplitude of the various imbalance parameters considered individually. Table 1, Figures 4 and 5 in the main report illustrate the major results.

4. IMPACT ON AC AND DC NETWORKS

This section reiterates basic notions concerning harmonics amplification in a network and explains the prominent role played by network damping, often ineffective at low harmonic frequency. A well-designed harmonic filter can significantly contribute to reinforcing low-order harmonic frequency attenuation and consequently controlling the level of harmonic voltages which are dangerous in both steady-state and transient operating modes. Filtering system design is consequently a key element when selecting insulation for the various converter station components.

5. DISTURBANCE CRITERIA

The selection of criteria defining the disturbance level is absolutely essential in studying the filtering system. A good criterion must obviously have a physical meaning - not always true of criteria used. Respect for one or more selected criteria must be associated with practical measures to be implemented.

One example, typical of numerous DC links, shows that, in practice, low-order harmonics are the most important in quantifying voltage distortion. Likewise, taking into account just the harmonics up to order 10 is enough to calculate the value of TIF (Telephone Interference Factor) and IT factors. In practice, non-characteristic harmonics above order 20 can be ignored, as long as high-pass damped filters are included in the station filtering system.

Based on the practical experience of applying various parameters, Working Group 14-03 recommends that the following criteria be used by electrical engineers :

- maximum level for each individual harmonic ;
- rms, value of total distortion.

In addition, to specify the maximum telephone interference level allowed, Working Group 14-03 recommends avoiding the IT criterion, which is nonetheless widely used in several link specifications. Instead, an equivalent interference current criterion should be used; this takes into account the frequency-dependent relation between harmonics currents circulating in a power line and a telephone circuit likely to be disturbed. This is especially important in high ground resistivity areas.

6. TRANSIENT OPERATING MODES

Filters can be designed to significantly improve the attenuation of transient operating modes for post-fault transmission restoration and to help keep harmonic overvoltages to a value that is economically acceptable in terms of equipment insulation.

When filters are used for transient overvoltage limitation, they must be designed so that dissipative components, resistors and lightning arresters can withstand the energy generated by maneuvers or failures, which must be specified.

7. SOLUTIONS SELECTED FOR RECENT LINKS

This section constitutes the most significant part of the report and gives extensive details as to selection criteria, as well as on technical filtering solutions adopted for 24 links commissioned over the last ten years.

The links studied are: ACARAY (Paraguay), DURNHOR (Austria), GOTLAND (Sweden), EDDY COUNTY (USA), ITAIPU (Brazil), CHATEAUGUAY (Canada), PACIFIC INTERTIE UPGRADE (USA), HIGHGATE (USA), OKLAUNION (USA), BLACKWATER (USA), MILES CITY (USA), MADAWASKA (Canada), 2 GW CROSS CHANNEL Link (England-France), INTERMOUNTAIN PROJECT (USA-Canada), QUEBEC-NEW ENGLAND (USA-Canada), SIDNEY (USA), CORSICA TAPPING (France), SACOI 2 (Italy-France), FENNOSKAN (Finland-Sweden), KONTISKAN 2 (Sweden-Denmark), VINDHYACHAL (India), GEZHOUBA-SHANGHAI (China), RIHAND-DELHI (India), McNEILL (Canada).

8. CONCLUSION

The various sources of non-characteristic harmonic generation are presented in this paper, along with their relative significance with respect to characteristic harmonics, taking into account resonance between the AC network and harmonic filters. Interactions with the DC part of the link and station controls are also indicated.

Harmonic behavior of converters operating under unbalance conditions should be considered as a well-known feature. Digital tools are available for analysis.

Non-characteristics harmonics are generated by a combination of the following parameters :

- unbalance in the three-phase voltage system in the AC network ;

- unbalance in conversion transformer reactance ;

- unbalance in delay angles at firing.

The first factor is the most important in links equipped with modern control-command units.

Low-order non-characteristic harmonic filters have been installed in several recent links. No link required the installation of a filter tuned to a non-characteristic harmonic above order 10.

To obtain cost-effective filtering performance, the expected imbalance ratio for the network is to be specified. 1% of the inverse component is a typical order of magnitude. From an economic perspective, it is very important to limit to a low value the scattering tolerance of transformer reactance between transformers and between transformer's phases. To calculate filtering values, a scattering value of 1 % seems reasonable, based on tolerances obtained in fabrication stages.

The addition of filters to limit resonance phenomena to a very low harmonic frequency increases financial investments and station losses. It is therefore economically important to know as precisely as possible the harmonic impedance of the network at low frequency, and particularly the resistive component of that impedance. In certain cases, it is important to control the damping of the network/filter combination in order to reduce the amplitude of temporary overvoltages, particularly in the event of transformer saturation.

Working Group 14-03 feels it is necessary to improve the knowledge of actual impedance and particularly the attenuation given by AC networks in the field of low order harmonics . Electricity utilities should play a major role in this difficult task.

1. INTRODUCTION

En 1979, le Groupe de Travail 14-03 a publié un rapport dans le n° 63 de la revue Electra : "Filtrage des harmoniques alternatifs et compensation de la puissance réactive pour le transport à courant continu - enquête générale". Ce rapport présentait en détail les différents problèmes induits par le filtrage des harmoniques et la compensation de puissance réactive dans les stations de conversion utilisées pour le transport électrique en continu. Le rapport indiquait également les méthodes utilisées pour résoudre ces problèmes dans les 18 liaisons en service ou en construction à cette époque. En ce qui concerne la puissance réactive, le Groupe de Travail 14-03 publiait en 1983 un second rapport sur l'état de l'art des techniques de compensation : "Utilisation des compensateurs statiques ou synchrones dans les réseaux à courant continu".

Durant les dix dernières années, du fait de ses avantages économiques et techniques le transport en courant continu a connu un accroissement considérable de ses applications. Ainsi, en 1988, 68 liaisons ont été identifiées par le Groupe de Travail 4 du Comité d'Etudes 14 (Liaison à courant continu) de la CIGRE : 35 liaisons sont en exploitation et 33 sont à l'état de projet décidé ou en construction.

Pour ce qui concerne le filtrage des harmoniques, il a été considéré nécessaire de faire une nouvelle enquête basée sur l'expérience acquise dans les liaisons les plus récentes. L'objet du présent rapport est de mettre à jour les informations déjà publiées dans le n° 63 d'Electra. Il présente en particulier les méthodes utilisées pour résoudre les problèmes provoqués par les harmoniques non-caractéristiques de faible rang (inférieur au rang treize). On rappelle que les harmoniques caractéristiques sont ceux engendrés par un convertisseur supposé idéal. Dans le cas des installations modernes utilisant des ponts dodécaphasés, il s'agit coté réseau alternatif, des harmoniques de rang 11, 13, 23, 25 , soit de rang général 12 k ±1 Par oppositions les autres harmoniques émis sont appelés non-caractéristiques.

2. L'IMPORTANCE DES HARMONIQUES NON-CARACTERISTIQUES

Ce chapitre présente les raisons pour lesquelles les problèmes induits par les harmoniques non-caractéristiques, s'ils ne sont pas nouveaux, présentent une importance accrue dans un certain nombre de liaisons récemment mises en service :

- tendance à ce que la puissance transmise en courant continu devienne élevée par rapport à la puissance des réseaux à courant alternatif interconnectés par la liaison en courant continu. La grandeur caractéristique de problèmes potentiels est le rapport de court-circuit, soit le rapport : puissance de court-circuit/puissance convertie en continu. Dans certains réseaux, il n'est plus rare d'observer des rapports de court-circuit voisins de 3, voire moins.

- existence dans le réseau alternatif d'une résonance à une fréquence harmonique non-caractéristique de rang faible. Problème qui apparaît dans les réseaux comportant des câbles ou de longues lignes aériennes. Par ailleurs l'amortissement apporté par le réseau tend à devenir d'autant plus faible que la fréquence de résonance est basse.

- tendance à compenser localement, dans la station de conversion, toute la puissance réactive absorbée par les convertisseurs (Q = 0,6 P en pratique). Cela tend à diminuer la fréquence de résonance réseau/bancs de condensateurs.

Tous les facteurs décrits précédemment contibuent à amplifier les harmoniques de faible rang, donc les harmoniques non-caractéristiques. En régime permanent, l'amplitude des harmoniques non-caractéristiques de rang 2 à 10 est, pour des ordres de grandeur réalistes des facteurs les provoquant, du même ordre de grandeur que celle des harmoniques caractéristiques de rang plus élevé.

En régime transitoire, consécutif à un défaut d'isolement du réseau ou à une réjection de charge, la saturation des transformateurs provoquée par la surtension temporaire due aux bancs de compensation de réactif, provoque aussi la génération d'harmoniques non-caractéristiques. Leur effet doit être pris en compte pour coordonner les isolements de la station de conversion, tout particulièrement dans le cas d'un rapport de court-circuit de faible valeur.

3. GENERATION DES HARMONIQUES NON-CARACTERISTIQUES

Le chapitre est consacré à une présentation des paramètres qui gouvernent la génération d'harmoniques non-caractéristiques. Tous les déséquilibres de tension, d'impédance dans le réseau ou dans les transformateurs de conversion, de rapports de transformation entre les transformateurs à couplage étoile-triangle ou étoile-étoile, d'angles de retard à l'amorçage des 12 valves d'une unité de conversion, contribuent à engendrer des harmoniques non-caractéristiques. D'autres facteurs y contribuent aussi comme l'ondulation du courant continu provoquée par d'autres stations du réseau à courant continu ou par couplage à la fréquence fondamentale avec une ligne à courant alternatif proche de la ligne à courant continu ainsi que la présence dans le réseau alternatif d'autres sources de perturbations harmoniques.

Les influences particulières des différents types de déséquilibres sont examinées au plan des rangs d'harmoniques engendrés et de l'amplitude de ces harmoniques. Le rapport présente notamment les résultats d'une étude spécifique de sensibilité de la génération des harmoniques non-carctéristiques à l'amplitude des divers paramètres de déséquilibre considérés individuellement. Les Tableau 1 et figures 4 et 5 du rapport principal illustrent les principaux résultats de cette étude.

4. EFFETS SUR LES RESEAUX ALTERNATIF ET CONTINU

Le chapitre rappelle les notions de base concernant les phénomènes d'amplification des harmoniques dans le réseau et le rôle important que joue l'amortissement du réseau, d'ailleurs souvent peu efficace à basse fréquence harmonique. Un filtre d'harmonique bien conçu peut notablement contribuer à renforcer l'amortissement de fréquences harmonique de faible rang et ainsi maîtriser le niveau de tensions harmoniques dangereuses aussi bien en régime permanent qu'en régime transitoire. La conception du système de filtrage intervient donc dans le choix des isolements des divers matériels de la station de conversion.

5. CRITERES DE PERTURBATION

Le choix des critères caractérisant le niveau de perturbation est absolument déterminant pour l'étude du système de filtrage. Un bon critère doit évidemment présenter une signification physique - ce n'est pas toujours le cas de certains critères en usage- ; le respect du ou des critères retenus doit pouvoir faire l'objet de mesures pratiques à mettre en oeuvre.

On montre, grâce à un exemple représentatif de nombreuses liaisons à courant continu, que, en pratique, les harmoniques de rang faible sont les plus importants pour quantifier la distorsion de la tension. De même la prise en compte des seuls harmoniques jusqu'au rang 10 suffit à calculer la valeur des critères TIF (Telephone Interference Factor) et IT. En pratique, les harmoniques non-caractéristiques de rang supérieur à 20 peuvent être négligés, pourvu que des filtres amortis passe-haut soient prévus dans le système de filtrage de la station.

En se fondant sur l'expérience pratique d'applications de différents critères, le Groupe de Travail recommande que l'usage des critères suivants soit préferentiellement adopté par la communauté des électrotechniciens :

- niveau maximal de chaque harmonique individuel ;

- valeur efficace de la distorsion totale.

Par ailleurs, pour spécifier le niveau de perturbation téléphonique maximale admissible, le Groupe de Travail déconseille l'usage, pourtant répandu dans les spécifications de plusieurs liaisons, du critère IT, au profit d'un critère de courant équivalent perturbateur qui tienne bien compte du couplage, dépendant de la fréquence, entre les courants harmoniques circulant dans une ligne d'énergie et un circuit téléphonique exposé à un risque de perturbation. Ceci est particulièrement important dans les zones à forte résistivité de terre.

6. REGIMES TRANSITOIRES

Les filtres peuvent être conçus pour améliorer efficacement l'amortissement des régimes transitoires de restauration du transit après défaut et pour contribuer à maintenir les surtensions harmoniques à une valeur acceptable économiquement par l'isolation des matériels.

Si l'on fait usage de filtres pour cette dernière fonction de limitation des surtensions transitoires, ils doivent être conçus de façon à ce que les éléments dissipatifs, résistances et parafoudres supportent l'énergie résultant des manoeuvres ou des défauts, qui doivent être spécifiés.

7. EXAMEN DES SOLUTIONS ADOPTEES DANS DES LIAISONS RECENTES

Ce chapitre constitue la partie la plus importante du rapport et donne un grand nombre d'informations détaillées sur les critères de choix ainsi que sur les solutions techniques de filtrage adoptées dans 24 liaisons mises en service depuis 10 ans.

Sont ainsi passées en revue les liaisons de ACARAY (Paraguay), DURNROHR (Autriche), GOTLAND (Suède), EDDY COUNTY (Etats-Unis), ITAIPU (Brésil), CHATEAUGUAY (Canada), PACIFIC INTERTIE UPGRADE (Etats-Unis), HIGHGATE (Etats-Unis), OKLAUNION (Etats-Unis), BLAKWATER (Etats-Unis), MILES CITY (Etats-Unis), MADAWASKA (Canada), 2 GW CROSS CHANNEL Link (Angleterre-France), INTERMOUNTAIN PROJECT (ETats-Unis), QUEBEC-NEW ENGLAND (Etats-Unis-Canada), SIDNEY (ETats-Unis), CORSICA TAPPING (France), SACOI 2(Italie-France), FENNOSKAN (Finlande-Suède), KONTISKAN 2 (Suède-Danemark), VINDHYACHAL (Inde), GEZHOUBA-SHANGHAI (Chine), RIHAND-DELHI (Inde), McNEILL (Canada).

8. CONCLUSIONS

Les diverses sources de génération d'harmoniques non-caractéristiques sont présentées dans ce rapport ainsi que leur importance relative comparée aux harmoniques caractéristiques, en tenant compte des résonances entre le réseau alternatif et les filtres d'harmoniques. Les interactions avec le coté continu de la liaison et le contrôle-commande des stations sont aussi examinées.

Le comportement harmonique des convertisseurs fonctionnant dans des conditions de déséquilibre doit être considéré comme bien connu. Des outils numériques sont disponibles aujourd'hui aux fins d'analyse.

Les harmoniques non-caractéristiques sont engendrés par combinaison des paramètres suivants :

- déséquilibre du système triphasé de tensions du réseau alternatif ;

- déséquilibre des réactances des transformateurs de conversion ;

- déséquilibre des angles de retard à l'amorçage.

Parmi ces trois facteurs, le premier est le plus important dans les liaisons équipées de contrôles-commandes modernes.

Dans plusieurs liaisons récentes, des filtres d'harmoniques non-caractéristiques de rang faible ont été installés. Dans aucune liaison il n'a été nécessaire d'installer un filtre accordé sur un harmonique non-caractéristique de rang supérieur à 10.

Pour obtenir des performances de filtrage économiques, il est nécessaire de spécifier précisément le taux attendu de déséquilibre du réseau. 1% de composante inverse constitue un ordre de grandeur typique. Il est aussi d'une très grande importance économique de limiter à une faible valeur la tolérance de dispersion des réactances de transformateur entre appareils et entre phases. Pour le calcul du filtrage, la prise en compte d'une valeur de dispersion de 1% parait tout à fait raisonnable aujourd'hui, en se basant sur les tolérances obtenues en fabrication.

L'ajout de filtres pour limiter les résonances à une fréquence harmonique très faible augmente l'investissement et les pertes de la station. Il est donc économiquement important de connaître le plus précisemment possible l'impédance harmonique du réseau à basse fréquence et en particulier la composante résistive de cette impédance. Dans certains cas la maîtrise de l'amortissement de l'ensemble réseau/filtre est importante pour réduire l'amplitude des surtensions temporaires, en cas de saturation des transformateurs en particulier.

Un besoin d'amélioration de la connaissance de l'impédance réelle et en particulier de l'amortissement apporté par les réseaux alternatifs, dans le domaine des basses fréquences harmoniques, est ressenti par le Groupe de Travail. Les compagnies d'électricité devraient jouer un rôle important dans cette tâche ardue.

TABLE OF CONTENTS

1. INTRODUCTION

In 1979, Working Group 14.03 published a paper in issue 63 of Electra : 'AC Harmonic Filters and Reactive Compensation for HVDC - A General Survey' **[1.1]**. This paper presented in detail the problems associated with harmonic filtering and reactive power compensation for converter stations used for HVDC transmission. The paper also indicated the methods adopted to overcome these problems in the 18 links in operation or under construction at that time. With regard to reactive power, Working Group 14.03 published a further report in Electra n° 91, 1983 on the state of the art in compensation techniques : 'Use of Static or Synchronous Compensators in HVDC Systems' **[1.2]**.

In the past 10 years, due to the specific technical and economic advantages of HVDC, there has been a considerable increase in its application. Thus, by 1988, 68 links had been identified by Working Group 04 of Study Committee 14 (DC Links) of CIGRE : 35 links in operation and 33 links in the detailed planning or construction stage.

With regard to harmonic filtering, it has been considered necessary to make a new survey based on the experience gained from the most recent links. The object of this paper is to update the information published in issue 63 of Electra. It presents in particular the methods used to solve the problems due to low order non-characteristic harmonics (below 11th).

2. IMPORTANCE OF NON-CHARACTERISTIC HARMONICS

In the operation of a DC converter connected to a perfectly symmetrical AC system, with no unbalance in the commutation reactance and with equal firing angles in all component valves, the current in the AC side of the converter contains only harmonics of $6\,k \pm 1$ order (where k is an integer) for a 6-pulse bridge or $12\,k \pm 1$ order for a 12-pulse unit. These are the characteristic harmonics of the converter. All other orders of harmonics are described as non-characteristic harmonics (refer to section 3) **[2.2, 2.3, 2.4]**.

The problems caused by non-characteristic harmonics are not new. The survey published in 1979 indicated that, in some links, a non-characteristic harmonic (3, 5 or 9) justified the subsequent addition of a specific resonant filter (Lydd, Benmore, Vancouver, Eel River), although other links have operated perfectly satisfactorily without such filters.

For several reasons, including mainly the unbalance of the system voltage and of the network and transformer impedances, the current spectrum of DC converters contains practically all characteristic and non-characteristic harmonics to some extent.

A parallel resonance always occurs between the network impedance (which is inductive at low frequencies) and the impedance of any shunt capacitor banks or filters (which are capacitive below their tuned frequencies). This response can cause an unacceptable voltage distortion at a low order non-characteristic harmonic frequency. The effective impedance of the converter, reflecting the HVDC transmission system and controls, may also have a notable influence and, together with DC and/or AC side resonances, may also amplify the higher order harmonics produced by the converter.

In some recent HVDC projects, the problem of non characteristic harmonics has been aggravated for a number of reasons :

1) the power transmitted by the DC link may be high compared to the power of the AC networks which are interconnected ; a low short circuit level of the network corresponds either to a system with few machines or to the converter station being supplied via a long AC line.

2) the AC system itself may resonate at low order non-characteristic harmonic frequencies, particularly when a network includes cables or long AC overhead lines which provide substantial capacitive generation. The damping of a network tends to increase with increasing frequency. For low order harmonics the limiting impedance angle can be high and severe resonances can occur.

3) because of the limited capacity of alternators to deliver reactive power and/or in order to control the voltage profile of the AC network, the tendency in new schemes is to compensate totally, by local means, the reactive power absorbed by the converters. The high capacity output of the filters or shunt capacitor banks decreases the resonant frequency with the network.

In steady state operation, the low order non-characteristic harmonic currents 2 to 10 can reach the same order of magnitude as those of the characteristic currents of higher order. Transients such as energization and fault clearance cause transformer saturation which temporarily generates additional low order non-characteristic harmonic currents. The overvoltages which result must be considered for insulation coordination, especially for weak AC systems.

A further reason for renewed interest in non-characteristic harmonics is that a parallel resonance can amplify considerably several harmonics at different times ; the critical frequency varies as a function of the AC system and of the configuration and number of filters or capacitor banks in operation. In general therefore, remedies cannot be adopted only for one specific harmonic, but must avoid unacceptable amplification for a number of frequencies.

The following sections explain the mechanisms for the generation of non-characteristic harmonics in steady state and transient conditions, the major role played by the network impedance and the consequences in terms of AC-DC interaction. Finally, the solutions adopted to solve specific problems of low order harmonics are included in descriptions of some of the most recent projects.

3. GENERATION OF NON-CHARACTERISTIC HARMONICS

3.1 Sources of non-characteristic harmonics

The following sources of non-characteristic harmonic currents should be considered, not only individually, but in the more likely combinations in which they can occur simultaneously :

1) Presence of a negative phase sequence component of fundamental frequency AC voltage at the converter bus ;

2) Different transformer reactances between phases in each 6-pulse unit ;

3) Different average transformer reactances between bridges in a 12-pulse unit ;

4) Non - √ 3 turns ratio between converter transformers of a 12-pulse unit ;

5) Ripple on the direct current, due to unbalances at other converter stations on the HVDC system ;

6) Ripple at fundamental frequency on the direct current, due to induction from AC transmission lines parallel to the HVDC transmission line ;

7) Presence of harmonic distortion due to other sources in the AC system ;

8) Random firing unbalance of the valves, due to random processes in the control and valve firing systems.

The above list consists only of original sources of system asymmetries or unbalances. Many other unbalances may be observed on an operating system, but are not necessarily true sources. One example is firing-angle unbalance. This is usually due to regulator action in response to harmonics on the input signals, which are in turn due to one of the above true sources. Such firing-angle unbalance can be much greater than that due to random processes in the firing equipment.

3.2 Influence of various asymmetries

Each type of asymmetry creates a distinctive pattern of harmonics, as described below :

1) a negative phase sequence voltage, which causes unbalance in the AC supply voltage, will create odd-triplen harmonics (3, 9, 15...), which are positive phase sequence rather than the zero-sequence normally attributed to the triplens on power systems ;

2) different average commutation reactances and non- √3 turns ratio between converter transformers (Yy and Yd) for a 12-pulse converter generate those harmonics of a 6-pulse converter, which are not present in a ideal 12-pulse converter (i.e. 5, 7, 17, 19,...) ;

3) different phase reactances within a 6-pulse converter group give rise to odd-triplen harmonics (3, 9, 15, ...), including zero-sequence components if the primary of the converter transformer is grounded and the secondary is delta-connected ;

4) random firing unbalance can generate all harmonic orders, including even harmonics ;

5) fundamental-frequency ripple induced on the converter DC side current can cause a full spectrum of harmonics on the AC side, including zero-sequence if the converter transformer is grounded. This is due to a consequent offset-saturation of the converter transformer, described

in detail in [3.1]. In practical applications, this ripple must be kept very low by design factors on the DC side of the system, so is unlikely to cause a significant impact on AC filter design.

For each of these effects the magnitude of non-characteristic harmonic currents will vary almost linearly with the source amplitude over the practical range of variation of the relevant parameters.

3.3 Magnitudes of various asymmetries

It is usual to consider a valve firing accuracy within ± 0.2 degree, but with modern technology it should not be difficult to achieve ± 0.1 degree.

Some suppliers use their previous good experience to assume a tolerance of ± 1 % on transformer nominal reactances although the transformer manufacturer may only be willing to guarantee ± 5 %.

For some recent schemes (e.g. the Cross Channel Scheme and Itaipu), values from 0,5 % to 2 % for negative phase sequence voltage have been considered in the filter calculation. The voltage unbalance in any country is usually determined by factors such as the extent of development of railway and single-phase rural electrification, and by the degree of transposition of transmission lines.

3.4 Relative importance of various parameters

References [3.4, 3.8, 3.9] give detailed discussions on the calculation methods for non-characteristic harmonics and the influence of asymmetries on the generation of those harmonics. Reference [3.9, 3.10] describe computer programs to calculate non-characteristic harmonics.

Appendix 1 contains results of a sensitivity analysis made by the Working Group for five individual causes of unbalanced operation and described in Table 1.

Table 2 presents comparative values of low order non-characteristic harmonic currents based on this analysis. These were all done neglecting ripple on the direct current.

Appendix 2 discusses the effects of interactions between the AC and DC systems.

4. EFFECTS OF THE AC AND DC SYSTEMS

4.1 Magnification of low order harmonics

The following simplified reasoning permits an understanding of the magnification phenomenon. Figure 1 shows the equivalent scheme of one converter supplied by an AC system of internal impedance Zr (and corresponding admittance Yr) at the frequency h.

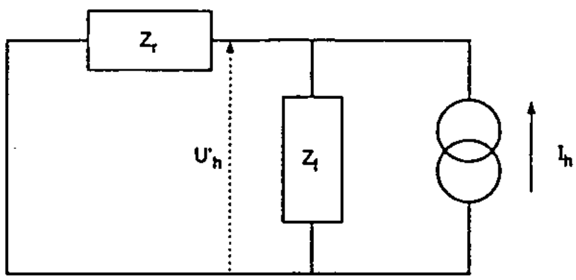


Figure 1 : Equivalent Scheme of converter/AC system/Filter at harmonic frequencies

- for fundamental and low order harmonics this impedance is usually predominantly inductive giving an admittance :

$$Y_r = G_r - jB_r$$

- in the absence of any filters or compensation, the harmonic current Ih of the converter generates, at the point of connection, an harmonic voltage of amplitude :

$$U_h = Z_r I_h = I_h / Y_r$$

- when capacitor banks or filters of admittance Y_f, at frequency h are installed in order to absorb part of the harmonic current, the harmonic voltage at the point of connection becomes :

$$U'_h = I_h / (Y_r + Y_f)$$

- the admittance of a normal filter bank is predominantly capacitive i.e.

$Y_f = jB_f$

Thus :

$U'_h = I_h/(G_r - jB_r + jB_f)$

When $B_r = B_f$, the harmonic voltage is limited only by the system resistance, which is often not accurately known but may be quite small. In general, when $Y_r + Y_f < Y_r$ the harmonic distortion is magnified, the magnification factor being :

$U'_h/U_h = Y_r/(Y_r + Y_f)$

Consequently, a low order non-characteristic harmonic current, which has no practical adverse effect in the absence of the capacitor or filter banks, can be amplified to give a voltage greater than the filtered harmonics.

Two types of remedy are possible :

1) limiting non-characteristic harmonic currents by reducing the causes of unbalance (closer tolerances on transformer reactances, transposition of lines etc.) ;

2) detuning the resonance or limiting the magnification factor to an acceptable value by adding one or more specific filters in order to modify the AC side impedance.

The second type of remedy presents an additional advantage with respect to harmonics which are pre-existing in the network. The usual assumption is that the network seen from the converter behaves like a harmonic voltage generator. The equivalent scheme of Figure 1 shows that the harmonic voltage at the point of connection of the converter is equal to U_h in the absence of the filters and to $U'_h = U_h * Z_f/(Z_f + Z_r)$ in the presence of filters.

The ratio U'_h/U_h is equal to $Z_f/(Z_f + Z_r)$ or $Y_r/(Y_f + Y_r)$, i.e. :

the magnification factor defined before. In practice, a detailed analysis of the resonance condition must take into account the harmonic impedance of the converter itself.

The parallel resonance frequency is highly sensitive to the system impedance ; where this impedance can vary greatly, it may be disadvantageous to use narrow-tuned resonant filters. The use of filters with a wider pass-band can give more damping but such filters must be designed to avoid an unacceptable increase of the losses at fundamental frequency. Second order type damped filters are therefore unsuitable for very low order non-characteristic harmonics.

Another possible cause of harmonic magnification is the response factor of the converter control system which may cause the converter to present an equivalent negative resistance for some low order harmonics. Investigations on a simulator are necessary to study this problem correctly.

In conclusion, it may be necessary to reduce the magnification factor by one or more specific filters in order to limit :

1) the adverse effects of the low order non-characteristic harmonic currents generated by the converters ;

2) the magnification of certain pre-existing harmonic voltages in the AC system.

4.2 Importance of the AC network resistance at low frequency

When considering classical resonant filters, taking into account the damping of the AC network generally allows the use of smaller sized filters when a target of maximum harmonic voltage has been specified. This size reduction is a function of the maximum phase angle (Θ_h max in Figure 2) of the network impedance at frequency h and is expressed by :

$1/(1 + \cos \Theta_h max)$

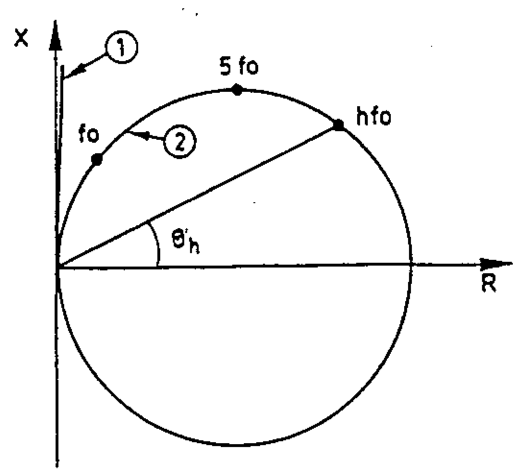


Figure 2 : AC system Impedance damping at low frequencies

1 - Purely inductive system

2 - Real system impedance for filter performance studies : Θ max depends on h.

The filtering performance of damped filters for high frequencies does not depend much on the converted power or on the network impedance, the latter being generally higher than the filter impedance.

On the other hand, when designing a damped filter for stronger damping of a low order harmonic voltage, it is essential to know accurately the network impedance at low frequencies. It is necessary to ensure that connecting the filter in parallel with the network impedance has a positive effect on the harmonic voltage and avoids any excessive amplification of harmonic voltages of other orders, especially those which are close. These requirements must be fulfilled while keeping an acceptable level of losses.

Calculations of the transient overvoltages resulting from the energization of the converter transformers and of compensation equipment also depend on the damping of the AC network at low frequencies. Figure 3 illustrates the results of analysis of overvoltages due to switching of a second-order high-pass filter bank versus the switching instant and shows how the damping representation of the network itself may be influential. Such an analysis requires, on the one hand, the determination of the network impedance locus for its various configurations and, on the other hand, adequate modelling of this impedance, especially for the resonant frequencies between the AC network and the filters. Transient conditions are discussed further in Section 6.

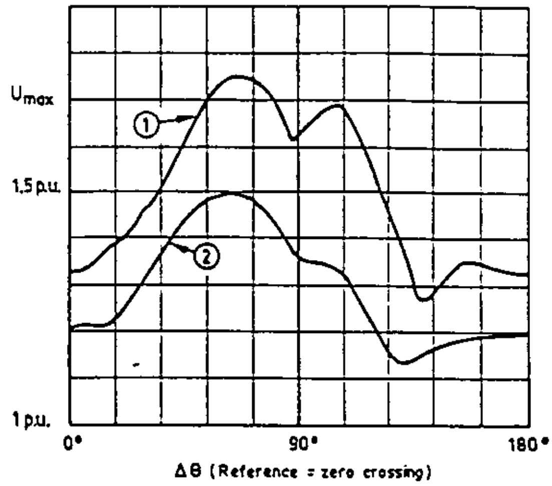


Figure 3 : Influence of system damping on transient overvoltage calculated maximum overvoltage versus point-on-wave at energizing the first 150 MVar filter bank of a converter station

1 - Purely inductive system
2 - Real system impedance (400 kV/4 GVA/50 Hz)

5. DISTURBANCE CRITERIA

The choice of disturbance criteria is very important because it will influence filter design [4.1, 4.6]. In HVDC schemes where no allowance was made for non-characteristic even harmonics in the design criteria, they will nevertheless be present in practice and may be included in the results of measurements. Appendix 3 summarises the main criteria in normal usage and gives the relevant definitions.

5.1 Characteristics of a good disturbance criterion

1) it should have a physical meaning and should give a value which is strongly correlated to the severity of the disturbance.

2) it should be possible to verify that the criterion is met by measurements, and to compare the design target for a new project with real values obtained for schemes in operation.

5.2 Effects of including non-characteristic harmonics

Appendix 4 demonstrates by a typical example, how the numerical value obtained using different criteria depends on which harmonics are taken into account.

From this and other examples the following conclusions can be drawn :

1) for distortion, the lowest harmonics are the most important ones ;

2) calculations of TIF and IT will be reasonably accurate even if non-characteristic harmonics only up to the 10th are taken into account :

3) non-characteristic harmonics above the 20th can be neglected provided that high pass damped filters are used.

5.3 Recommended criteria

5.3.1 Voltage distortion

It is recommended that the root-sum-square (rss) based total distortion criteria should be used but not the arithmetic one. The reason is that the rss distortion corresponds to the power of the harmonics and is therefore more closely related to the severity of the disturbance. The arithmetically added distortion does not correspond to any physically verified disturbance. Furthermore, the use of the arithmetic distortion criterion would lead to a requirement for high accuracy, even in the calculation of very small harmonics ; as there are so many of these, the arithmetic criterion does not converge, which means that the value reached depend very much on the number of harmonics taken into account. In addition, it is not possible to verify this criterion by practical measurements.

<u>It is strongly recommended to use the following criteria</u>:

1) maximum level of any single harmonic ;

2) rss based summation for total distortion.

In most cases it will be sufficient to include all harmonics of order up to 25.

The maximum values of individual harmonics generally occur for different conditions. It is therefore necessary to clarify whether the rss summation should use those values of individual harmonics which are simultaneously present, or the non-coincidental maximum values of each harmonic.

5.3.2 Telephone interference

The concept of IT product into a node of a meshed transmission system has no general validity or meaning although it has been used in several projects. Nevertheless, since the publication of the previous Electra paper in 1979, it has been identified that in certain cases, particularly where earth resistivity is high, there is a justification to limit the magnitudes of harmonic currents flowing in particular transmission lines which run close to telephone lines. It is necessary to take into account frequency-dependent coupling of the telephone circuits from the balanced and zero sequence harmonic currents and this can be accomplished by defining an 'equivalent disturbing current' appropriate to the particular transmission line.

6. TRANSIENT CONDITIONS

Performance during major disturbances is an important aspect of HVDC system design. AC side filters must be designed to survive the most severe disturbance anticipated for the HVDC link. In addition, filters can be designed in such a way as to improve the recovery performance of the HVDC system.

6.1 Role of AC filters for improving performance

Following severe disturbances, several types of distortion can exist on the AC voltage. The sources of such distortion are transformer magnetising current, the natural transient response of the AC network and possible oscillations on the direct current, reflected through to the AC side of the converter. Such distortion can interfere with the recovery of the HVDC system, and can create high overvoltage conditions.

AC filters can be designed to reduce the level of distortion on the AC voltage to help the recovery process and to reduce the possible levels of overvoltage. Such filters are tuned to frequencies in the range of 2nd to 4th harmonic and may include resistors and/or non-linear components to help damp out or limit the transient response.

6.2 Design considerations

Low-order harmonic filters require special consideration for rating of components, particularly resistor and arrester energy capacity. Transients of greatest impact are typically :

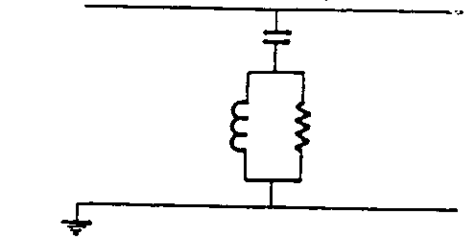
1) energization of nearby transformers or reactors ;
2) three-phase fault, cleared at the worst time for offset saturation of nearby transformers ;
3) extended single-phase faults, including those at the remote end of the HVDC system.

Such transients can produce high energy absorption in arresters and resistors. These components can require many hours to cool down, so consideration must be given to repeated events.

ACARAY (Paraguay)

Réseau ANDE 50Hz Paraguay
ANDE system 50Hz

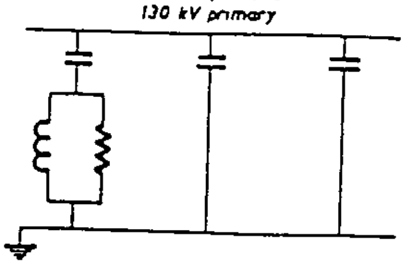
220 kV primaire
220 kV primary



Q =	
F.R.P.	17

Réseau COPEL 60Hz Brésil
COPEL system 60Hz Brazil

130 kV primaire
130 kV primary

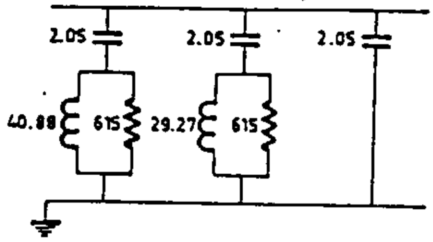


Q =			
F.R.P. =	18	9	9

DÜRNROHR (Autriche - *Austria*)

Côté Tchécoslovaquie
Czechoslovakian side

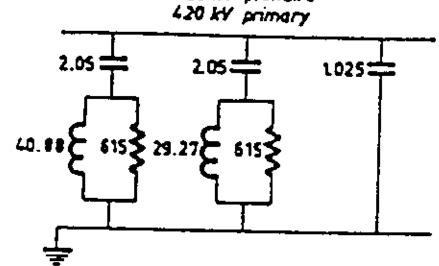
420 kV primaire
420 kV primary



Q =	4.36	5.15	
F.R.P. =	103	103	103
n =	11	13	

Côté Autriche
Austrian side

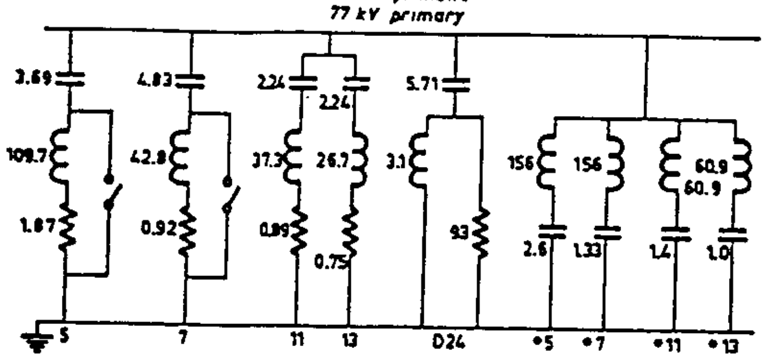
420 kV primaire
420 kV primary



Q =	4.36	5.15	
F.R.P. =	103	103	52
n =	11	13	

Liaison GOTLAND / *GOTLAND HVDC links*

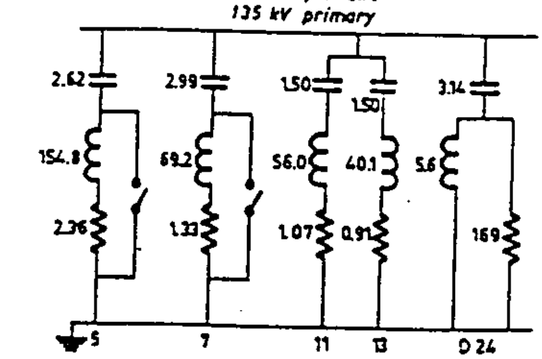
Gotland 50 Hz
77 kV primaire
77 kV primary



	5	7	11	13	D24	•5	•7	•11	•13
Q =	65	65	80	84	4	70	70	70	70
F.R.P. =	6.8/6.5	8.7/8.5	4.0	4.0	10.1	5	2.5	2.6	1.9

• Pour le fonctionnement avec la liaison Gotland de 130 MW seulement
For operation with the Gotland 130 MW link only

Vastervik 50 Hz
135 kV primaire
135 kV primary



	5	7	11	13	D 24
Q =	70	70	90	90	4
F.R.P. =	15.6/15.0	12.5/12.1	8.7	8.6	18.0

Légende :

- (condensateur) valeur en µF - *value in µF*
- (inductance) valeur en mH - *value in mH*
- (résistance) valeur en Ω - *value in Ω*

F.R.P. = Puissance réactive fondamentale triphasée Mvar
Fundamental reactive power Mvar 3 phase

Q = Coefficient de qualité du filtre
Quality factor of the filter

N = Nombre de filtres de chaque type
Number of filters of the represented type

7. REVIEW OF RECENT SCHEMES

The schemes are presented in the approximate order where they entered or are planned to enter into operation. Data on filter design are detailled in tables 6-1 to 6-5 and single-line diagram for each scheme is shown on the page facing the description.

7.01 Acaray converter station

The Acaray back-to-back asynchronous tie is rated for 50 MW and interconnects the Brazilian and Paraguayan AC systems. The converter station is connected to the 220 kV, 50 Hz ANDE power system in Paraguay and to the 130 kV, 60 Hz COBEL grid in Brazil.

At both sides the converter station is equipped with a minimum AC filter configuration consisting of one high pass damped filter circuit. The filter at the 220 kV/50 Hz side is tuned to 12 harmonic, i.e. 600 Hz, with a nominal reactive power of 17 Mvar. The corresponding filter at the 130 kV, 60 Hz side is also tuned to 12 harmonic, i.e. 720 Hz with a nominal reactive power of 18 Mvar. In addition two shunt capacitor banks each 9 Mvar are connected to the 130 kV AC-bus.

The chosen design fulfills the specified performance limits which are :

	220 kV/50 Hz	130 kV/60 Hz
D_n	0.4 %	0.5 %
D	1 %	1 %
Deff	0.7 %	0.7 %
TIF	28	28

7.02 Dürnrohr

The 550 MW back-to-back converter station in Dürnrohr, Austria was commissioned in 1983. The converter station is designed to connect the Western European UCPTE and Eastern European CMEA AC systems. At both sides of the converter station two high-pass damped AC filter circuits are installed, one for 11 and the second for 13 harmonic. The rating of each was 103 Mvar. In 1988 the rating of both harmonic filters at the Czechoslovak side was reduced to 92.5 Mvar according to operational experience. In addition the Austrian side of the converter station is equipped with a 51.5 Mvar shunt capacitor bank and the Czechoslovakian side with a 103 Mvar shunt capacitor bank **[5.1, 5.2]**.

With respect to specified limits of ± 60 Mvar reactive power exchange at the Austrian/Czechoslovakian border, reactive power control is performed by switching of AC-filters and capacitor bank, and also by increased reactive power absorption capability of the converters using firing/extinction angles under light load conditions.

The performance limits are D_n = 0.7 %, Deff = 1.0 % and THFF = 1.0 % over the whole range of operation.

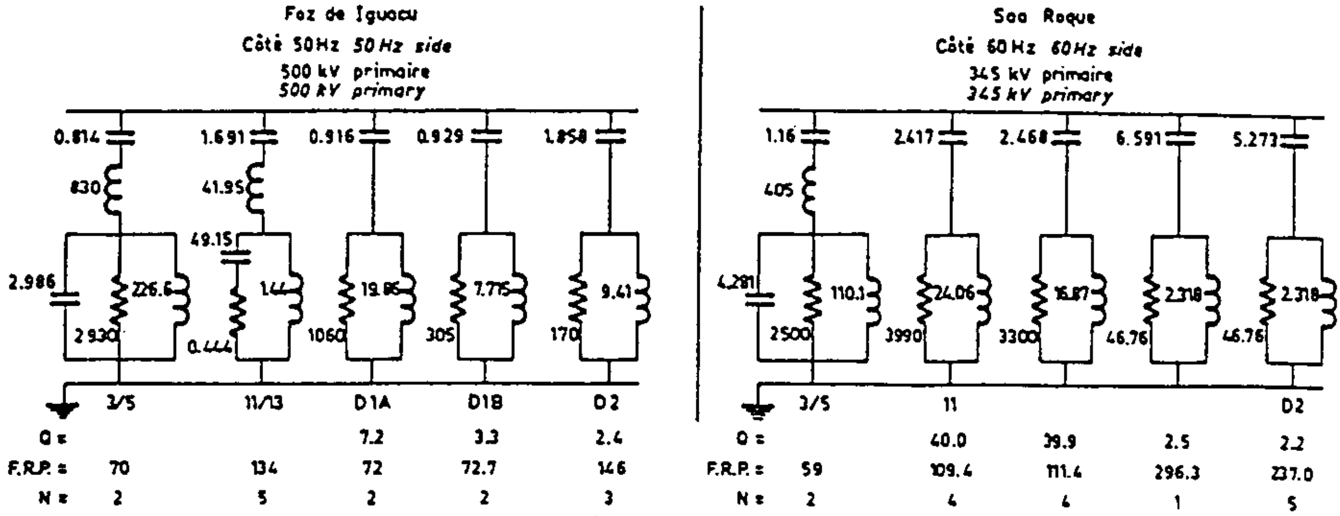
7.03 Gotland

The original Gotland HVDC link entered into service in 1954 with two converters of 10 MW each. In 1970 this link was uprated to 30 MW by adding a further 10 MW converter. In october 1983 a new link rated at 130 MW (150 kV, 910 A) was added. The winter overload rating of the new link is 160 MW, 1.23 pu.

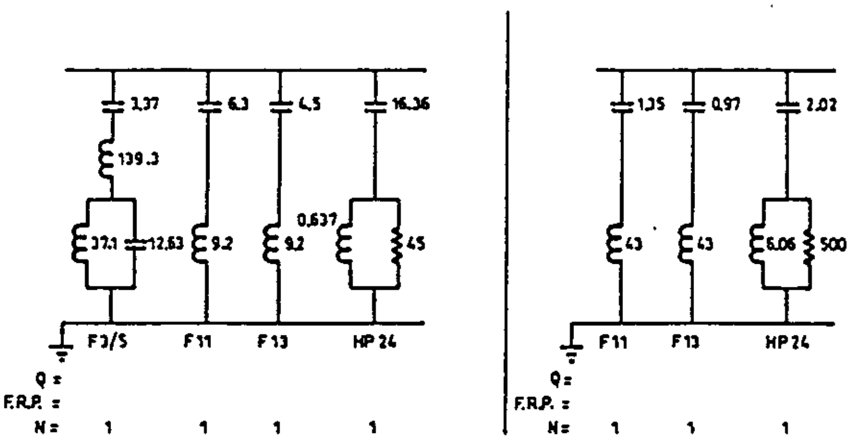
For the new link no spare transformers are provided but the scheme is suitable for 6-pulse operation at half the rated voltage if one of the transformers has been lost. Therefore 5th and 7th harmonic filters are provided for both stations. However, in order to minimize the losses during normal operation the reactors and resistors are short-circuited by disconnectors. The presence of 5th and 7th harmonic filters also allows for co-operation of the two HVDC links during peak loads, as the first link consists of three 6-pulse converters.

Gotland Island does not have local generation and therefore two synchronous compensators are located at the Gotland terminal to provide reactive power compensation, short circuit power and inertia. The previous filters cannot be used together with the new HVDC link due to the difference in ratings but are retained to enable operation of the old link even when the new filters are not available. The terminal on the mainland is located at Västervik. The Västervik network can stand operation of the old 30 MW link without filters in an emergency and therefore no filters are needed for this old link.

ITAIPU (Brésil - *Brazil*)



CHATEAUGUAY (CANADA)



<u>Légende</u> :
- (condensateur) valeur en µF - *value in µF*
- (inductance) valeur en mH - *value in mH*
- (résistance) valeur en Ω - *value in Ω*

F.R.P. = Puissance réactive fondamentale triphasée Mvar
Fundamental reactive power Mvar 3 phase
Q = Coefficient de qualité du filtre
Quality factor of the filter
N = Nombre de filtres de chaque type
Number of filters of the represented typn

7.04 Eddy County (no description available)

7.05 Itaipu

The criteria adopted for harmonic distortion were TIF, 1 % for D_n and 4 % for the arithmetic sum D. The non-characteristic harmonic problems were related to distortion and overvoltages, caused mainly by the harmonics of 3rd, 5th and 7th orders **[5.3, 5.4, 5.5]**.

To prevent distortion problems double-tuned 3/5th harmonic filters are installed at both stations. No filter was provided for the 7th harmonic, since it was concluded that the high distortion value calculated for this harmonic were caused by some very unfavourable representation of the Paraguayan system, which were considered highly unlikely to occur in practice. As to overvoltages, the problem was basically solved by the use of ZnO arresters with adequate energy discharge capability, aided by the low order harmonic filters.

The filters were designed using the worst combination of transformer reactances. Using the measured reactance values for some of the first transformers to be tested, the distortion factors were recalculated and were much lower than the limits indicated above. These new calculations also confirmed that the 7th harmonic filter was not necessary. The need to avoid excessive step changes of voltage limited the sizes of filters in several cases.

7.06 Chateauguay

7.06.1 Original filter arrangement

The Chateauguay 1000 MW HVDC back-to-back converter station interconnects the 315 kV AC system of Hydro-Quebec with the neighbouring 120 kV AC system of the Power Authority of New York (NYPA). Special emphasis is placed on the availability of the power transmission. For this reason the converter station is split up into two fully independent blocks each rated for 500 MW. Because of weak AC system conditions at the 120 kV side an additional SVC is installed on the 120 kV AC bus in Chateauguay. The nominal operating range of this SVC is from 150 Mvar inductive to 120 Mvar capacitive.

At both sides of the converter station the AC filters are split up into two identical branches each comprising

120 kV side	315 kV side
1x 3/5 filter	---
1 x 11 filter	1 x 11 filter
1 x 13 filter	1 x 13 filter
1 x 26 high pass filter	1 x 26 high pass filter
-----	1 x shunt capacitor bank

The total installed reactive power of all the AC filters amounts to 2 x 168 Mvar = 336 Mvar at the 120 kV side and to 2 x 313 Mvar = 626 Mvar at the 315 kV side.

7.06.2 Later Filter Expansion

After commissioning and final acceptance of the converter station it was decided to upgrade the transmission capacity of the 120 kV AC-lines feeding the NYPA system. For this purpose two additional capacitor banks, each of 135 Mvar, have been installed at the 120 kV line entries at Chateauguay substation. These circuits are tuned to the second harmonic and are of the high-pass damped type, because of the weak AC system conditions which make it necessary to damp low-order non-characteristic harmonics caused by saturation of transformers in the Chateauguay substation.

The chosen design fulfills the specified performance requirements on both sides of the link which were :

D_n 1.0 % (but with low-order filter, 0.5 %)

D 4.0 %

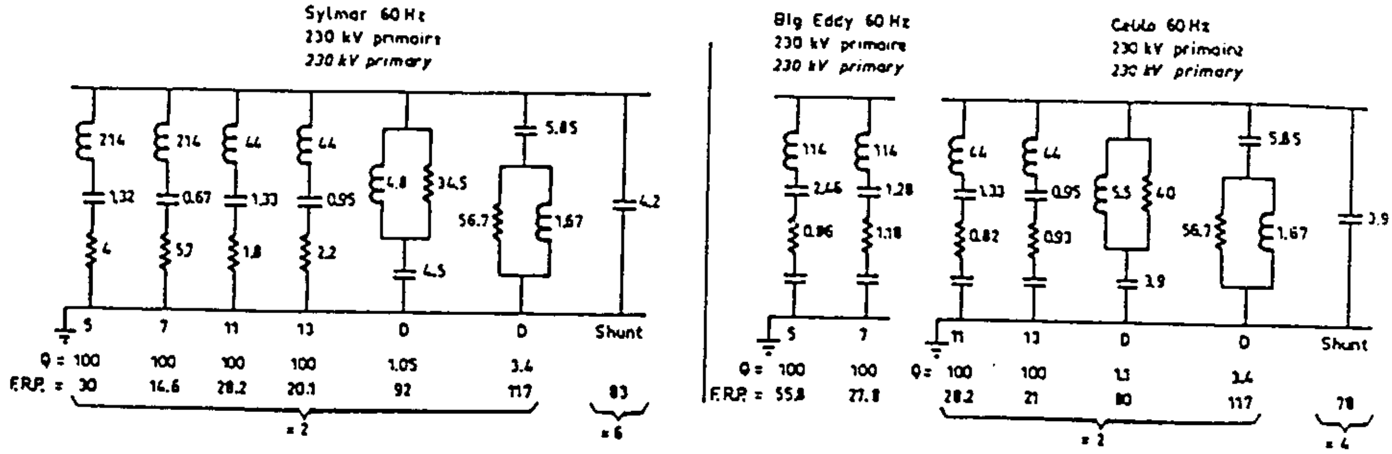
TIF 20

IT 25000

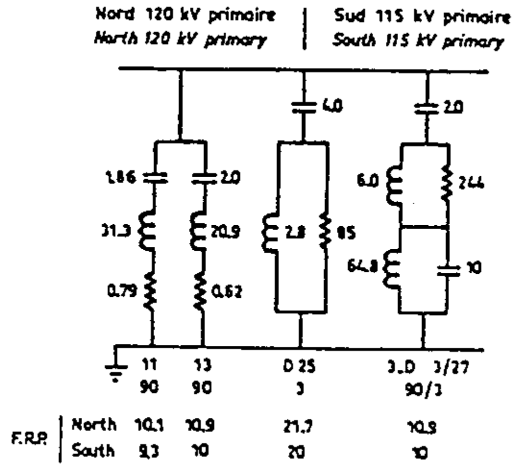
<u>Special design aspects involved in this project may be summarised as :</u>

- 3 % negative phase sequence on the 120 kV side ;
- low order harmonic filters on the 120 kV side ;
- high-pass damping for the characteristic harmonics of higher order ;
- damping of low order harmonic overvoltages under transient conditions due to transformer saturation phenomena.

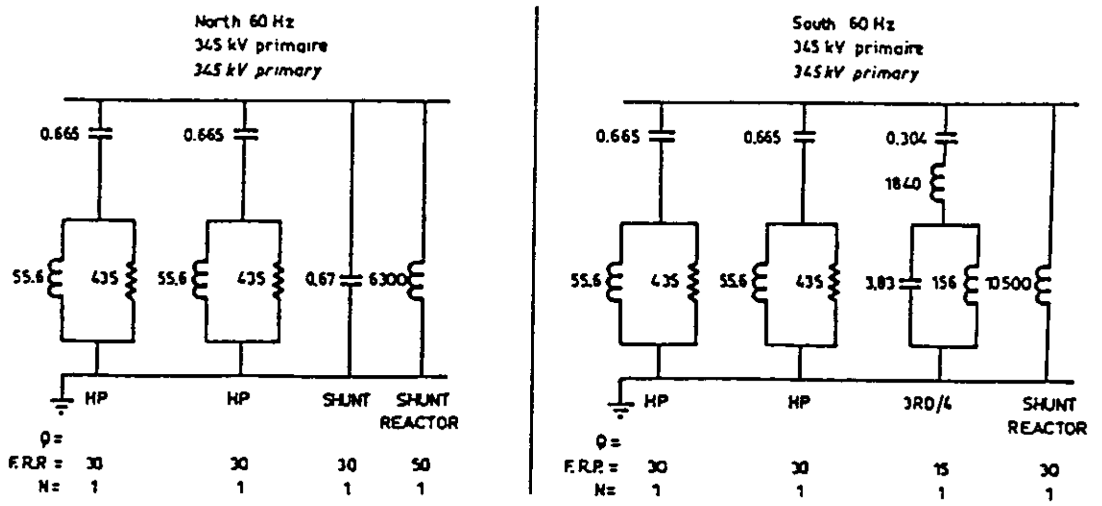
PACIFIC INTERTIE UPGRADE PROJECT (Etats-Unis _ *USA*)



HIGHGATE 60 Hz (Etats-Unis _ *USA*)



OKLAUNION HVDC (Etats-Unis _ *USA*)



Légende :

- (condensateur) valeur en μF _ *value in μF*
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F.R.P. = Puissance réactive fondamentale triphasée Mvar
Fundamental reactive power Mvar 3 phase

Q = Coefficient de qualité du filtre
Quality factor of the filter

N = Nombre de filtres de chaque type
Number of filters of the represented type

7.07 Pacific Intertie Upgrade

The Pacific Intertie Upgrade project, commercially operated since February 1985, increased the capacity of the bipolar Pacific HVDC Intertie transmission line from 1600 MW to 2000 MW by adding two 6-pulse, 100 kV DC converter bridges (one in series with each pole) to each terminal. The direct current, at 2000 A, remains unchanged by this upgrading.

Before the Upgrade project, Sylmar converter station was equipped with 5, 7, 11, 13 and high-pass harmonic filters on each pole. To this, the project added a pair of 117 Mvar supplementary high-pass filters (one per pole) tuned to the 27 harmonic. Counting the Mvar supplied by these supplementary filters, the total reactive power available at Sylmar is 1086 Mvar. This makes additional shunt compensation unnecessary despite the increase in system power transfer capacity. Furthermore, the Upgrade project does not require any low order harmonic filters.

7.08 Highgate

The Highgate converter station interconnects the Hydro Quebec and Velco AC transmission systems. It is a back-to-back station consisting of two 12-pulse converters, 3600 A, 56 kV and 200 MW. The filter configurations are identical on both sides of the converter station. The filters consist of two 11/13 branches, one high pass branch for 25 and one double tuned 3/27 harmonic branch. The 3 harmonic filter is needed because of harmonics from the AC network. Furthermore, there are 4 shunt capacitors banks to fulfill the reactive power requirements.

7.09 Oklaunion

The Oklaunion 200 MW back-to-back scheme is the first of two electrical interconnections planned between the Electric Reliability Council of Texas (ERCOT) and the Southwest Power Pool (SPP). The purpose of the tie is to allow the economical transfer of power between ERCOT and SPP companies.

Two 30 Mvar high-pass filters tuned to 828 Hz were installed on both the north and south buses to absorb the 11, 13 and other higher order characteristic harmonics of the 12-pulse converter station. A double-tuned 3/4 harmonic filter was installed on the south side to protect against transient ferroresonance overvoltage. The north side required a 30 Mvar capacitor bank in addition to the two 30 Mvar filters for voltage support. A 30 Mvar reactor was installed on the south side due to the capacitance of the long AC line and the 3/4 harmonic filter.

7.09.1 Original AC System

Initially the Oklaunion HVDC Tie was interconnected with a single 115 mile, 345 kV AC line on the south side and a single 67 mile, 345 kV AC line on the north side. System short circuit capacities were calculated to be 678 MVA and 730 MVA respectively. In an effort to maintain fundamental AC voltage in the range of ± 5 %, the high-pass filters were staged, the first filter switched prior to start-up and the second filter automatically switches on at 40 % power and off at 35 % power. The shunt reactor on the south side and the capacitor bank on the north side were automatically switched in response to primary AC voltage sensing.

TNA studies demonstrated that severe overvoltages could occur during blocking of the DC tie while all 60 Mvars of filter capacitors were on line. The installation of a double-tuned 3/4 harmonic filter was shown significantly to reduce AC voltage after the blocking and also decrease the current absorption and energy dissipation of the bus arresters.

Field measurements indicated higher than expected non-characteristic fifth harmonic voltages on the north side. Fifth harmonic current measurements and additional voltage measurements were taken which indicated that the harmonic was coming from the AC system and not the DC tie. Though the design objective of 1 % for individual distortion was exceeded (1.25 to 1.7 %), the total distortion remained within the design objective of 2.0 %.

7.09.2 Present AC System

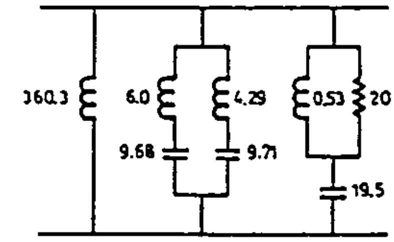
A 162 mile, 345 kV AC line and 50 Mvar reactor have been added to the north side. A 52 mile, 345 kV AC line, 250 MVA 345 kV/138 kV autotransformer and 640 MW coal fired generating unit have been added to the south side.

The DC tie is now normally operated with the 3/4 harmonic filter on the south side and 30 Mvar capacitor on the north side disconnected. The second HP filter is now automatically switched on at 55 % power and off at 40 % power.

A reduction of the fifth harmonic distortion on the north side was observed with the addition of the second 345 kV line and 50 Mvar reactor. However, the fifth harmonic increased on the south side to approximately 1.5 % with the addition of the 345/138 kV auto-transformer and second 345 kV line due to a mild resonance.

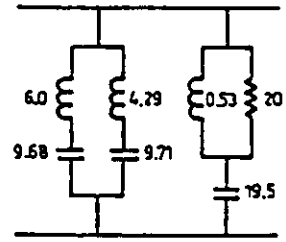
BLACKWATER (Etats-Unis _ *USA*)

New Mexico
côté 60 Hz _ *60 Hz side*
60 kV tertiaire _ *60 kV tertiary*



	Shunt reactor	11 13	HP 26
Q =			
F.R.P. =		26.5	26.5
N =	1	2	2

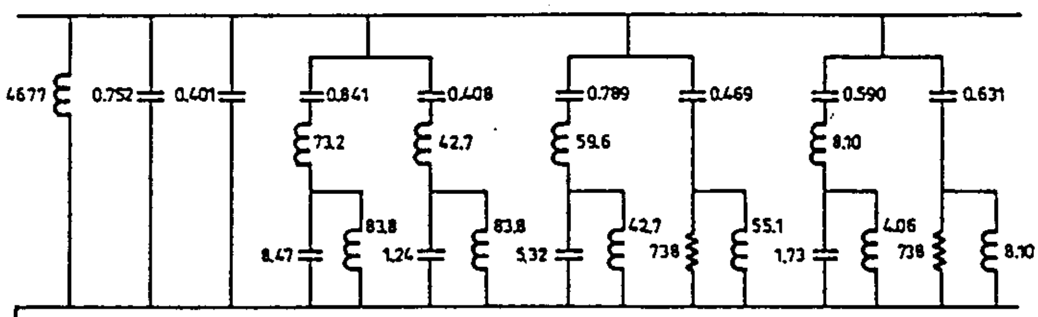
Southwest P.S.
côté 60 Hz _ *60 Hz side*
60 kV tertiaire _ *60 kV tertiary*



	11 13	HP 26
Q =		
F.R.P. =	26.5	26.5
N =	2	2

MILES CITY (Etats-Unis _ *USA*)

East/West 60 Hz / 60 Hz
230 kV primaire / 230 kV primaire
230 kV primary / 230 kV primary



	SHUNT REACTOR	SHUNT	SHUNT	3/11	7/23	5/13	HP18	25/47	HP36
Q =									
F.R.P. =	30	15	8	17	8	16	9	12	13
N East =	2	4	1	1	1	1	1	1	1
N West =	2	2	1	1	1	1	1	1	1

Légende :
- (capacitor) valeur en µF _ *value in µF*
- (inductor) valeur en mH _ *value in mH*
- (resistor) valeur en Ω _ *value in Ω*

F.R.P. = Puissance réactive fondamentale triphasée Mvar
Fundamental reactive power Mvar 3 phase
Q = Coefficient de qualité du filtre
Quality factor of the filter
N = Nombre de filtres de chaque type
Number of filters of the represented type

With the addition of a second 345/138 kV autotransformer some detuning of this resonance and decrease in fifth harmonic are expected.

7.10 Blackwater

The 200 MW Blackwater HVDC back-to-back tie interconnects the 345 kV AC-system of the PUBLIC SERVICE COMPANY OF NEW MEXICO (PNM) and the neighbouring 230 kV network of the SOUTH WESTERN PUBLIC SERVICE COMPANY (SPS) in the Southwest of the USA. The Blackwater station is placed in the vicinity of a large 230 kV SPS substation connected to the PNM system via a long 345 kV AC-line. Without special provision, large variations of 345 kV busbar voltage would occur at the Blackwater station. For this reason the converter station is designed for continuous AC voltage control. This is achieved by automatically adopting appropriate operating points in the P-Q-diagram.

The var control capability of the Blackwater converters is more than 200 Mvar at minimum power transfer and more than 100 Mvar at nominal power transfer. Due to this extreme range of reactive power control resulting in extremely high firing/extinction angles for the converters, the AC filters are specially designed to meet the harmonic performance requirements.

At both sides, the AC filters are connected to a 60 kV bus fed from tertiary winding of the converter transformers. The choice of this configuration allows a fine splitting of filter units and additional var units as shown below. This results in a smooth filter control, which would not be possible if the AC filters are connected to the HV-busbars directly.

60 kV AC filters		PNM	SPS
2 x single tuned	(11)	2 x 13.25 Mvar	2 x 13.25 Mvar
2 x single tuned	(13)	2 x 13.25 Mvar	2 x 13.25 Mvar
2 x high-pass	(26)	2 x 26.5 Mvar	2 x 26.5 Mvar
2 x shunt reactors		2 x 26.5 Mvar	---
Total filters (rating) :		106 Mvar	106 Mvar

The chosen design fulfills the specified performance requirements for 1 % individual distortion, 2 % rss total distortion (2-50) and TIF not exceeding 30 within the whole range of operation.

The special design aspects for this scheme may be summarised as :

- AC filter connected to the 60 kV tertiary winding of the converter transformers.

- integrated Static var Control capability with greatly increased firing and extinction angles.

7.11 Miles City

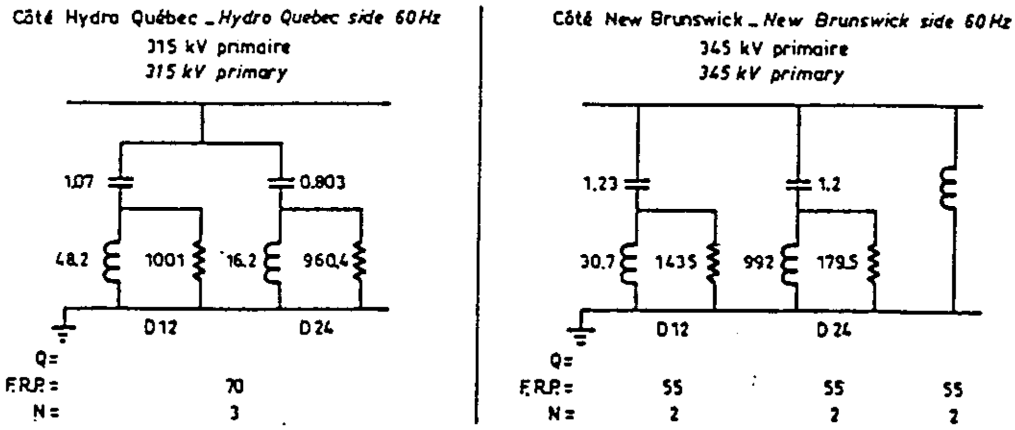
The 200 MW HVDC back-to-back Miles City converter station, located at Miles City, Montana, serves as an asynchronous connection between the east and west United States-Canadian AC transmission networks. The 12-pulse DC system is designed to operate at nominal 82 kV, 2476 A. The converter station is connected to the east and west AC systems at 230 kV. The weak AC systems at Miles City (550 MVA eastside and 400 MVA westside) required the use of special equipment and control features to meet all operating requirements for east-west and west-east power transfer. Incremental switching of shunt reactive equipment, converter transformer tap changer control, and extended thyristor firing angle control are used to meet AC system voltage control requirements and special zinc-oxide surge arresters are used to limit system dynamic overvoltages.

The station is designed with sufficient reactive power supply and absorption capability to meet the AC system and DC system requirements and allow control of AC bus voltages within defined limits. These features, together with the AC filters, influence the sizing of the reactive supply (shunt capacitors) and absorption (shunt reactor) equipment.

The shunt capacitors for the station are arranged in 15 and 8 Mvar banks and switched by interrupter switches with pre-insertion resistors. Four 15 and one 8 Mvar shunt capacitor banks are located on the west 230 kV bus. The AC harmonic filters provide 75 Mvar of the reactive requirements on each side of the station.

The shunt reactors are comprised of 30 Mvar three-phase units and switched by interrupter switches. Two shunt reactors are located on the east 230 kV bus and two on the west 230 kV bus.

MADAWASKA



Légende:
- valeur en µF _ *value in µF*
- valeur en mH _ *value in mH*
- valeur en Ω _ *value in Ω*

F.R.P. = Puissance réactive fondamentale triphasée Mvar
Fundamental reactive power Mvar 3 phase

Q = Coefficient de qualité du filtre
Quality factor of the filter

N = Nombre de filtres de chaque type
Number of filters of the represented type

The shunt reactors are switched in combination with shunt capacitor banks to limit the amount of reactive power to 15 Mvar switched in any one step. This limits the steady state voltage change due to reactive compensation to less than 2 %. Additional regulation of the reactive power is provided by controlling the reactive power consumption of the DC converters.

The AC harmonic filters are identical on each side of the station. They are comprised of four double-tuned and two high-pass filters on each of the east and west side 230 kV systems, and tuned to approximately the 3 and 11, 5 and 13, 25 and 47, high-pass 18 and high-pass 36 AC harmonics with à 60 Hz total reactive rating of 75 Mvar on each side.

Prior to designing the equipment for the AC harmonic filters, studies were undertaken to identify the component parameters required to meet the performance requirements. Several factors were used to ensure proper design of the AC harmonic filters including AC system harmonic impedance at harmonics up to n = 50, TIF limits, voltage distortion limits, valve firing angle unbalance and converter transformer reactance unbalance.

7.12 Madawaska

The 350 MW back-to-back converter at Madawaska station was put into service in 1985 in order to supply surplus energy from Hydro Quebec to the New Brunswick Electric Power Commission. Each converter consumes reactive power equal to approximately 60 % of its capacity under rated operating condition. The reactive power supply is controlled by switchable filter banks : three 70 Mvar banks (combined 12 and 24, HP filters in each bank) on the Hydro Quebec side and four 55 Mvar banks (two 12 and two 24, HP filters) on the New Brunswick side. On each filter bank a magnetic voltage transformer serves as a rapid discharge device to keep the filter ready for re-energization after the opening of its breaker **[5.6]**.

The filter configurations were designed for the following requirements under rated operating conditions : Dn = 1 %, D = 4 % and TIF = 20.

The worst unbalance conditions, maximum filter detuning and the system harmonic impedance were considered in the filter performance evaluation. The filters also have a certain overload capability to permit operation at high transmitted power with fewer filters in service. The size of each filter bank was limited to 70 Mvar on the Hydro Quebec side and 55 Mvar on the New Brunswick side in order to limit the voltage changes due to switching to about 3 % at the station bus under normal operating conditions. Since customer loads are electrically remote from Madawaska substation these voltage changes were considered acceptable.

Limitation of reactive power changes and voltage regulation at the AC buses are achieved by a special reactive bank switching control using a reactive-versus-active power control function overridden by an AC bus voltage control function. This control also handles reactor switching. Special care was taken to avoid hunting and conflict situations between the power and voltage control functions.

Under light local conditions on the DC system, two filter banks (one 12 and one 24) together with two shunt reactors are energised at the 345 kV bus in order to limit the reactive power flow into the AC network while improving the harmonic performance of the converter.

7.13 The 2000 MW Cross Channel link

7.13.1 French converter station : Les Mandarins

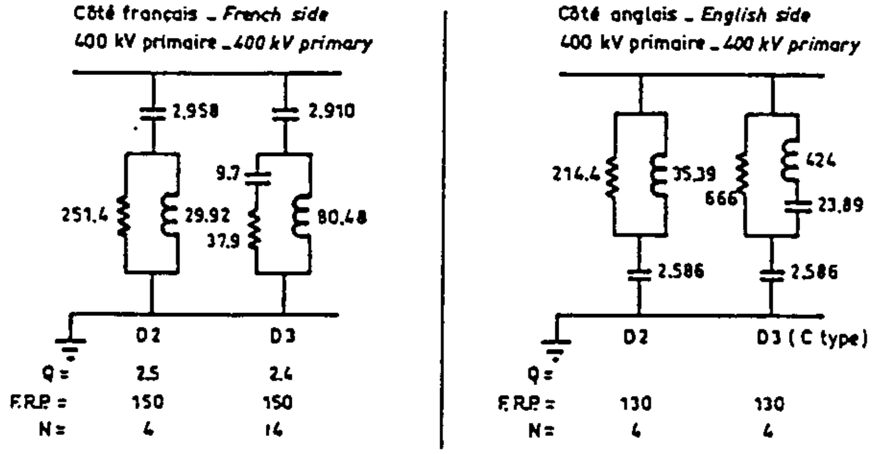
The harmonic impedance of the system at the converters bus was specified as the envelope of the polar diagrams (R,X), calculated for different configurations. They correspond to a range of short-circuit levels between 22 and 3.8 GVA, the latter being the case where one 1000 MW bipole is supplied by a long radial line.

The requirements for the AC system were that the contribution of the converter station to the total voltage distortion Deff should not exceed 1.6 %. Maximum levels Dn of 1.0 % and 0.6 % were specified for odd and even harmonic voltages respectively. A magnification factor of 3.3, which had been calculated, was also specified. It was also required that changes of the fundamental voltage at the station bus due to switching of capacitor banks, should not exceed 1 % in normal conditions, but could reach 4 % in the case of the long radial line. No consumers are supplied from the station bus in such a case **[5.7, 5.8, 5.9]**.

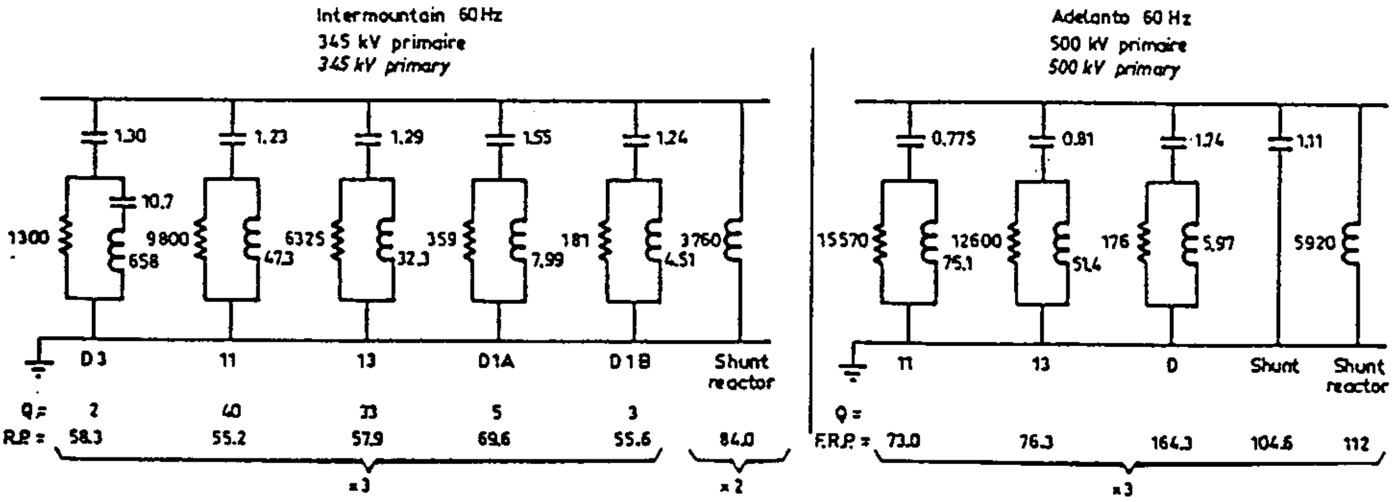
The calculations of non-characteristic harmonic currents generated by the converters were based on a maximum AC voltage negative phase sequence of 1.5 %. The maximum unbalance of converter transformer leakage reactances was considered to be 3 % i.e. the value guaranteed by the transformers manufacturer. A maximum unbalance of 0.25 degree was assumed for the firing angles of the valves.

IFA 2000 (Interconnexion France_Angleterre 2000 MW)

2000 MW CROSS CHANNEL LINK 2 (France_England interconnection 2000 MW)



INTERMOUNTAIN POWER PROJECT HVDC (Etats-Unis_ *USA*)



Légende :

valeur en µF _ *value in µF*

valeur en mH _ *value in mH*

valeur en Ω _ *value in Ω*

F.R.P. = Puissance réactive fondamentale triphasée Mvar
Fundamental reactive power Mvar 3 phase

Q = Coefficient de qualité du filtre
Quality factor of the filter

N = Nombre de filtres de chaque type
Number of filters of the represented type

With such assumptions, the expected values of 3, 5 and 7 harmonic currents were 0.4%, 0.7% and 0.6% of the fundamental current respectively. These levels are to be compared with the values of 3.7 % and 2.0 % of 11 and 13 harmonic currents.

Four of the 8 x 160 Mvar filter banks are second order high pass filters to absorb the characteristic harmonic currents. The other four are arranged as third order damped filter to provide sufficient damping to the parallel resonance at about 180 Hz. Third-order type filter have much lower fundamental losses than the second order type filter with the same effect in the range of 2 to 7 harmonics.

In some cases of severe AC system fault close to the station, the disconnection of a part of the filter can be automatically ordered in some tens of milliseconds, to limit the overvoltages if the d.c. link does not recover after the fault clearance.

7.13.2 English Convertor Station : Sellindge

The AC system requirements were that no individual harmonic voltage Dn should exceed 1 % of the 50 Hz voltage under normal conditions and the total rss voltage Deff should not exceed 1.5 %. Low order harmonic impedances were specified in the form of coherent tables for each normal and planned outage condition. To determine the appropriate impedance for each harmonic, polygons of AC network admittance were defined for harmonics of order 2 to 13, the points for particular network conditions being derived from the tables. For each filter combination one harmonic was assumed to be in resonance with the system and the point on the polygon giving the highest harmonic voltage was identified ; this point defined the system condition or outage most likely to give the maximum value for that harmonic. For this system condition, the impedances of all remaining harmonics in the range 2 to 25 were then selected from the appropriate table while remaining harmonic impedances in the range 26 to 49 were determined by the circle diagram method **[5.9]**.

It was considered necessary to limit 400 kV system overvoltages when DC load is interrupted. In order to achieve this limitation, two saturated reactor type Static Var Compensators (SVC) are connected to the 400 kV station bus. A third, identical, SVC is installed at a nearby substation.

Characteristic 12-pulse harmonic current were calculated on the basis of a nominal mid-Channel voltage of 270 kV DC and a pole current of 1852 A for the rated power of 2000 MW. Non-characteristic harmonics were based on 0.1° firing angle difference between 6-pulse groups and within each group, and also on a 5 % difference of reactance between phases of one transformer and between transformers. Fundamental negative phase sequence AC voltages of 0.5 % in England and 1.5 % in France were used to estimate the effects of system unbalance for performance, particularly with regard to the generation of third harmonic current. The third harmonic current caused by voltage unbalance was assumed to be independent of both DC load and of impedance seen from the convertor terminal ; it is not absorbed by delta windings because it is of positive sequence.

In addition, harmonic generation occurs within the three 150 Mvar SVCs. In order to co-ordinate with and complement the 400 kV convertor station filters, further filters for second and third harmonics are connected to the LV side of the compensator transformer.

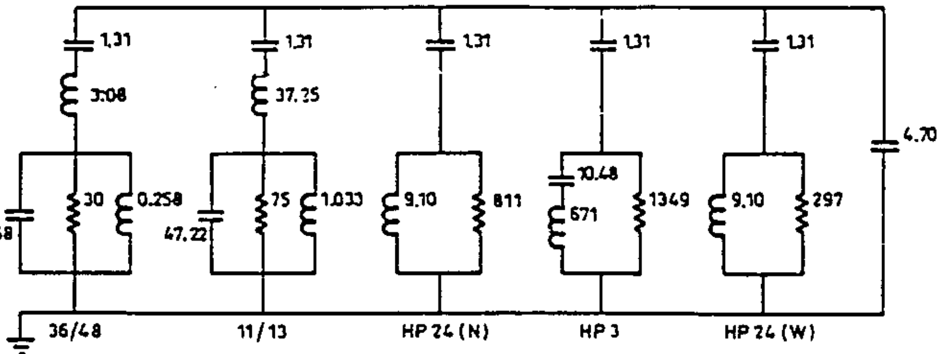
There are 8 x 130 Mvar filters, i.e. 4 per bipole, the size of each being influenced by the need to constrain voltage fluctuations on the AC system to around 1.5 % during filter switching. Large magnification factors for several system conditions are possible particularly at third harmonic and therefore half the filters have their minimum impedance at around 150 Hz. In order to incorporate damping without incurring a large fundamental power loss in the damping resistor, the 'C' type filter was adopted in which the resistor is bypassed by a 50 Hz tuned arm. The other filters are of second-order damped type to deal principally with the characteristic harmonics of 11 and 13 and higher orders.

7.14 The Intermountain Project (IPP)

The IPP HVDC scheme transmits power to Adelanto near Los Angeles from a 2 x 800 MW coal-fired power plant at Intermountain. One new feature for the IPP HVDC project is the possibility to overload one pole up to 1.5 pu power continuously. The short term overload is 2.0 pu in power which can be ramped down to 1.5 pu in about 7 minutes, matching the ramp down speed of the power plant.

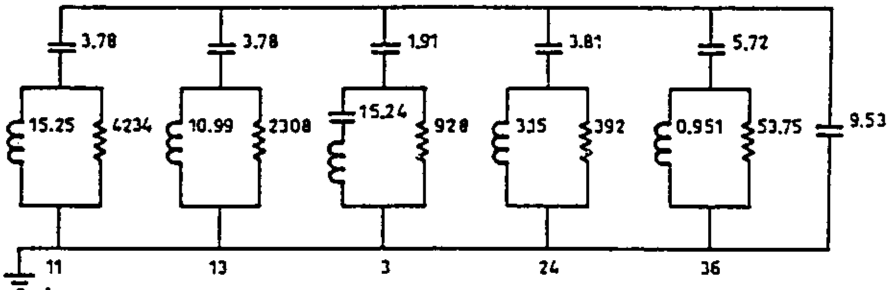
QUEBEC – *NEW ENGLAND* (Phase 2)

Radisson (Canada) 215 kV – 60 Hz



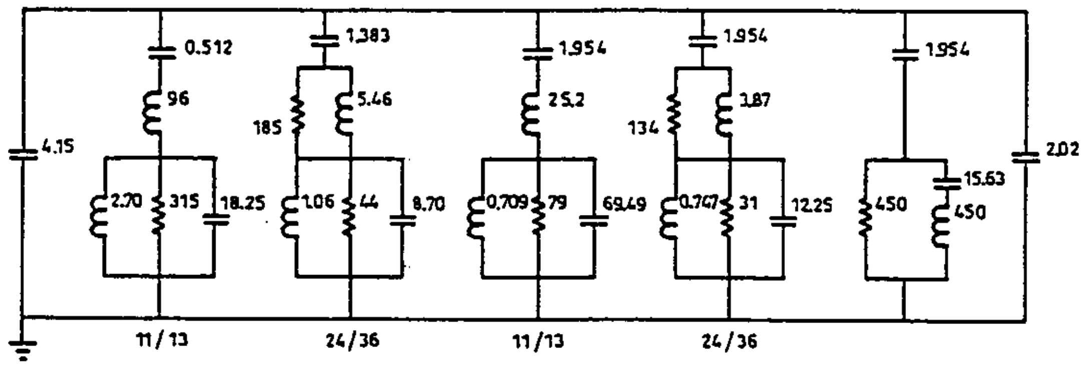
	36/48	11/13	HP 24 (N)	HP 3	HP 24 (W)	
Q =	10/10	30/30	9.0	2.0	3.5	
F.R.P. =	49	49	49	49	49	176
N =	2	6	2	4	4	2

Nicolet (Canada) 230 kV – 60 Hz



	11	13	3	24	36	
Q =	40	30	2.0	12.0	4.0	
F.R.P. =	76	76	38	76	114	190
N =	4	4	4	4	4	1

Sandy Pond (USA) 345 kV – 60 Hz



		11/13	24/36	11/13	24/36		
Q =							
F.R.P. =	186	23	62	87.5	87.5	87.5	90.5
N =	4	2	2	2	2	2	2

<u>Légende</u> :

- valeur en µF – *value in µF*
- valeur en mH – *value in mH*
- valeur en Ω – *value in Ω*

F.R.P. = Puissance réactive fondamentale triphasée Mvar
Fundamendal reactive power Mvar 3 phase

Q = Coefficient de qualité du filtre
Quality factor of the filter

N = Nombre de filtres de chaque type
Number of filters of the represented type

7.14.1 The Intermountain station

The convertor bipole, the three AC filter banks and the two IPP generators (through step-up transformers) are connected to the Intermountain 345 kV AC substation. The contribution from the surrounding AC network to the short-circuit power of the Intermountain station is lower than the contribution from the generators and the station may be operated without external connections.

Each AC filter bank has one branch tuned to 3 harmonic with a broad band damped characteristic which leads to fairly good filtering of 3 to 7 harmonics, tuned filter branches for the 11 and 13 harmonics and damped high pass filter branches tuned to the 24 and the 36 harmonics.

The important requirements for the low order harmonic filter are that individual distortion must be below 1.0 % and the sum of 5 and 7 harmonic currents in the generators must be below 0.7 % of the generator fundamental current, to avoid excessive 6th harmonic in the rotor.

The negative sequence AC voltage is specified to be at most 1.0 % of the positive sequence AC voltage. Monte-Carlo simulations were performed in which this and other unbalances were varied statistically for all extreme combinations of the main circuit parameters. Thus the 3, 5 and 7 harmonic currents at the nominal convertor power were found to be below 0.3 %, 0.11 % and 0.1 % respectively, with a confidence level more than 99 %.

Apart from the AC harmonic currents caused by the converter, the AC network and IPP generator harmonic impedances influence the harmonic distortion on the AC bus and the amount of harmonic currents penetrating the generators. The AC network harmonic impedance is specified within a line-circle diagram where the impedance angle is limited to - 85° and + 85° and the circle has its centre at 1000 and a radius of 1000 without any 3 harmonic branch, the 3 harmonic current at nominal convertor power would lead to a distortion of 2.1 % of the fundamental voltage, with sufficient filter branches in service to compensate for the HVDC reactive power consumption the AC network impedance chosen to maximise the distortion. The presence of third harmonic branches reduces the calculated 3 harmonic distortion to 0.5 % **[5.11]**.

During AC faults harmonic distortion is caused mainly by the saturation of the convertor transformers. If the AC network is weak, the resonance between the capacitive AC filters and the mainly inductive AC network impedance lies in the range between 2 and 4 harmonic. This resonance causes high distortion if the AC filter has low damping in this frequency range. The existence of 3rd harmonic filter branches increases the damping in the filter and the transient overvoltages are reduced.

The 3 harmonic branch reduces the impedance angle for the whole filter bank from approximately 90° to 69°, 81° and 85° for the 3, 5 and 7 harmonic currents respectively. The possibility of adverse parallel resonance between the filter and the AC network is thus reduced.

7.14.2 The Adelanto station

The two convertors and the three AC filter banks are connected to the 500 kV AC systems by four relatively short lines which give a quite stiff connection. Each filter bank consists of tuned filters for the 11 and 13 harmonics, a damped filter for the higher harmonics and a shunt capacitor. No low order harmonic filter is needed as the network is stronger and better damped than the generators in the Intermountain station.

7.15 Quebec - New England

7.15.1 Phase 1

In September 1986 a new DC system between Hydro Quebec and New England Hydro entered into service consisting of a 450 kV bipolar line with a capacity of 690 MW **[5.12]**.

Des Cantons terminal

To prevent interference in the AC network, Hydro Quebec chose the criteria Dn = 1 %, D = 4 % and TIF = 20. The final design of the filter consisted of a tuned 3, 11 and 13 and a high-pass branch. The 3 harmonic branch was installed for the purpose of meeting the arithmetic total distortion factor D.

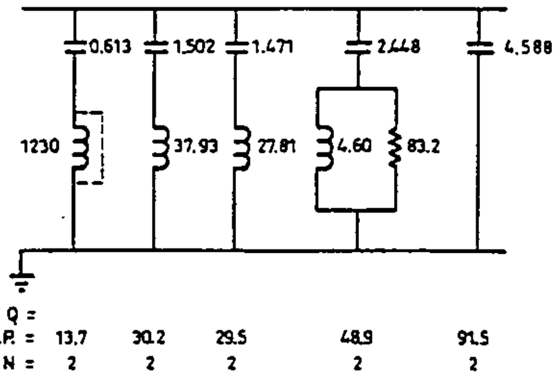
During the first year of service an abnormal overload was observed in the 3 harmonic branch during switching of converter transformer and the overload protection was activated. To solve the problem, it was decided to remove the inductor of the 3 harmonic filter and used this branch as a shunt capacitor bank. Since this modification, no problem has been reported on the AC harmonic filter.

QUEBEC – *NEW ENGLAND*

Côté Hydro Québec – *Hydro Quebec side 60 Hz*

230 kV primaire

230 kV. primary

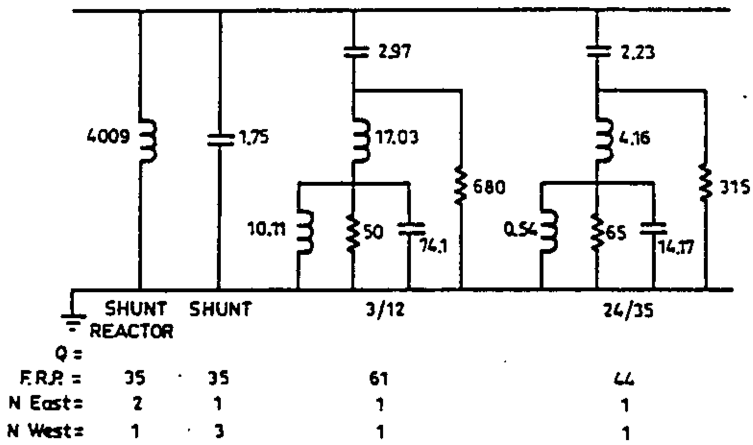


SIDNEY (Etats-Unis – *USA*)

East / West 60 Hz / 60 Hz

230 kV primaire / 230 kV primaire

230 kV primary / 230 kV primary



Légende:

- (capacitor) valeur en μF – *value in μF*
- (inductor) valeur en mH – *value in mH*
- (resistor) valeur en Ω – *value in Ω*

F.R.P. = Puissance réactive fondamentale triphasée Mvar
Fundamental reactive power Mvar 3 phase

Q = Coefficient de qualité du filtre
Quality factor of the filter

N = Nombre de filtres de chaque type
Number of filters of the represented type

7.15.2 Phase 2

This scheme is designed to transmit power from the hydro-electric generation of the James Bay region in the north of Quebec (Radisson converter) to the load centre of New England (Sandy Pond converter). The existing converter stations of Phase 1 (Des Cantons and Comerford) are to be connected into the multiterminal HVDC system and a fifth converter at Nicolet near Montreal will complete the scheme.

Radisson terminal

The filtering and reactive power scheme comprises six filter banks and two shunt capacitor banks. A third harmonic filter is provided to eliminate problems of low frequency resonance with the AC network. In order to fulfil the filter performance requirements at low power levels, two filter banks are equipped with very efficient filters for the higher order harmonics.

Nicolet terminal

The filtering and reactive power compensation scheme comprises eight filter banks, one shunt capacitor bank and three shunt reactors. A 3rd harmonic filter is included. All filters are of the damped type.

Sandy Pond terminal

The station is equipped with six filter branches of which two comprise a 3 harmonic filter bank in parallel with a shunt capacitor bank. The remaining four filter banks are divided into two large banks and two small banks, all equipped with a double-tuned 11/13 filter and a double tuned 24/36 filter. In addtion there are four shunt capacitor banks. The smaller filter banks are used for binary switching in order to maintain the voltage within the prescribed limits when switching the larger banks.

7.16 Sidney

The back-to-back Sidney Converter Station is installed at Sidney, Nebraska, to provide an energy interchange between the eastern and western United States power grids. It consists of 12-pulse HVDC system designed to operate at 50 kV and 4140 A and is capable of transferring 200 MW of power in either direction. Both networks that connect to the Sidney Converter Station are comprised of large generation and transmission systems operated asynchronously. Although the AC systems are large, electrically and geographically, the relative weakness of both AC networks at Sidney, required the use of special equipment and control features to allow a successful interconnection.

The converter station is designed with sufficient reactive power supply and absorption capability to meet the AC and DC system requirements and allow control of AC bus voltage within defined limits. These features, together with the AC filters, affect the sizing of the reactive supply (shunt capacitors) and absorption (shunt reactors) equipment. Additional reactive compensation is provided by controlling the reactive power consumption of the DC converter. Dynamic overvoltages are controlled by switching of special ZnO arresters **[5.13]**.

The shunt capacitors for the link are arranged in 35 Mvar banks and switched by interrupting devices. Three 35 Mvar shunt capacitor banks are utilised on the west 230 kV bus and one 35 Mvar shunt capacitor bank is located on the east 230 kV bus. The shunt banks include current limiting reactors for energisation and discharge devices to allow re-energisation within 10 seconds.

The shunt reactors are comprised of 35 Mvar three-phase units and are switched by interrupting devices. Two shunt reactors are located on the east 230 kV bus and one the west 230 kV bus.

The AC harmonic filters are comprised of two double-tuned filters on each of the east and west side 230 kV systems. The filters for each side are identical and tuned to approximately the 3/12 and 24/35 AC harmonics with a 60 Hz reactive supply of 105 Mvar.

Prior to designing the equipment for the AC harmonic filters, studies were undertaken to identify the component parameters required to meet the performance requirements. The design of the AC harmonic filters took into account the AC system network impedance, TIF limits, voltage distortion limits, valve firing angle unbalance and converter transformer reactance unbalance.

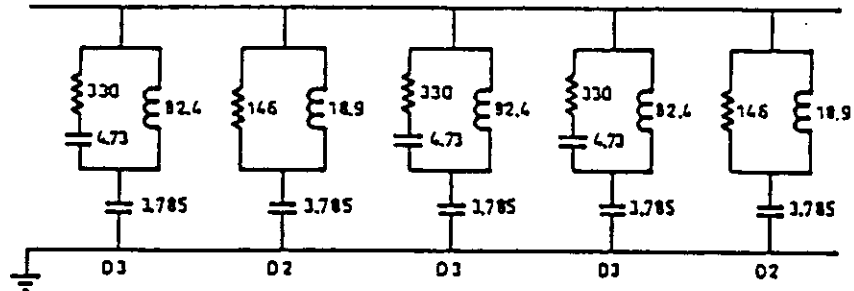
7.17 Corsica tapping

In the early 1980's, Electricité de France decided, with ENEL, to build a 50 MW tapping on the existing link between mainland Italy and the Island of Sardinia (SACOI). This link has an overhead section on the eastern coast of Corsica. Thus the converter tapping station has been located near the DC line and the consumer area of Bastia in the North-East of Corsica.

The existing link is monopolar and rated for 200 MW/200 kV DC. It comprises two 6-pulse mercury arc valve bridges at both ends and was designed

LUCCIANA (Corse _ Corsica)

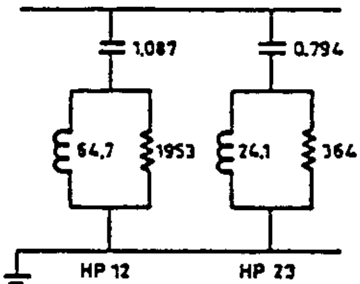
Prélèvement sur la liaison Sacoi _ *Topping on the Sacoi link*
90 kV primaire
90 kV primary



	D3	D2	D3	D3	D2
Q=					
F.R.P.=	10	10	10	10	10
N=	1	1	1	1	1

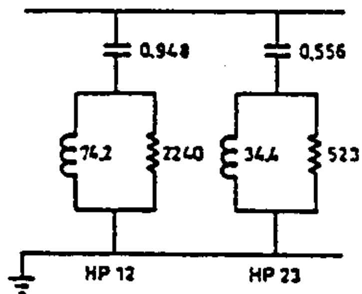
SACOI 2 (Italy)

Codrongianus 50 Hz
400 kV primaire
400 kV primary



	HP 12	HP 23
Q =		
F.R.P. =	55	40
N =	1	1

Suvereto 50 Hz
400 kV primaire
400 kV primary



	HP 12	HP 23
Q =		
F.R.P. =	48	28
N =	1	1

Légende :

- valeur en µF _ *value in µF*
- valeur en mH _ *value in mH*
- valeur en Ω _ *value in Ω*

F.R.P. = Puissance réactive fondamentale triphasée Mvar
Fundamendal reactive power Mvar 3 phase
Q = Coefficient de qualité du filtre
Quality factor of the filter
N = Nombre de filtres de chaque type
Number of filters of the represented type

to operate under 200 kV or 100 kV. The latter voltage corresponds to normal operation with only one bridge at both ends. The new tapping station, connected in parallel and equipped with thyristor-valves, is also designed to operate at both voltages, and independently of the power flow between the main stations. Rapid reversal switches are therefore installed.

In order to reduce the effects on the operation of the link of AC faults in Corsican AC network, the nominal margin angle gamma was chosen to be 40°. Thus the requirements for reactive power compensation is 50 Mvar at full load **[5.9]**.

The criteria adopted to define the number and types of the filters banks for compensation and filtering were the following :

- to compensate fully the reactive power absorbed by the station at full load ;
- to limit to 3 % the AC voltage changes at switching the filter banks in or out under normal conditions ;
- to limit individual harmonic voltage level in 12-pulse and 6-pulse operation (0.6 % for even harmonics in both case, 1 % for odd harmonics in 12-pulse operation and 2 % in 6-pulse operation).

In order to limit the reactive power transfer between the station and the Corsican system (minimum short-circuit level : 180 MVA), and to limit voltage changes at the station busbar, it was decided to install five 10 Mvar capacitor banks arranged in filters.

Several filtering solutions have been investigated such as resonant filters and damped high pass filters. As 6-pulse operation has to be considered, the major difficulty was to achieve filtering with the characteristic harmonic 5 and 7. Consequently, 3 banks have been dedicated to 6-pulse operation, for which power is limited to 25 MW (half power). The two other banks are used to achieve good filtering in 12-pulse operation.

The choice of damped filters allows good filtering on the AC system, the frequency of which can vary. The three filters for 6-pulse operation are third order type filters with a maximum admittance at 300 Hz. This structure reduces the losses, but has a higher cost than tuned filters. It was found that the filters for 12-pulse operation would be more efficient using the second order type structure. These have a maximum admittance at 600 Hz.

7.18 SACOI 2

The Sacoi 2 upgrade project consists of two new thyristor converter stations, replacing the existing ones equipped with obsolete mercury arc valves. At the same time the transmission capacity will be increased from 200 MW to 300 MW, with full utilization of the existing DC conductors (overhead lines and submarine cables) between Sardinian island and Tuscany (the mainland). Sacoi 2 is a monopolar three terminal link, as Sacoi 1 has been since 1987, after the commissioning of the Corsican tapping of Lucciana.

The same specifications were used for both the stations, Codrongianus in Sardinia and Suvereto in Tuscany. Individual harmonic voltage distortion less than 1 %, rss total distortion less than 2 % and THFF less than 0.9% have been specified in the harmonic range 2 to 50.

The calculation of harmonic current generation (characteristic and non characteristic) was performed considering $\pm$ 4 % transformer reactance tolerance, ± 0.2 % converter firing unbalances, and high firing angle operation (43°) when the link is operated at reduced voltage (75 %) in heavy salt polluted conditions. In this case the current is limited to 70 % in order to limit the reactive consumption.

"Base" impedance sectors have been defined for each harmonic n, with reference to minimum and maximum short circuit impedances, by using the following formulae :

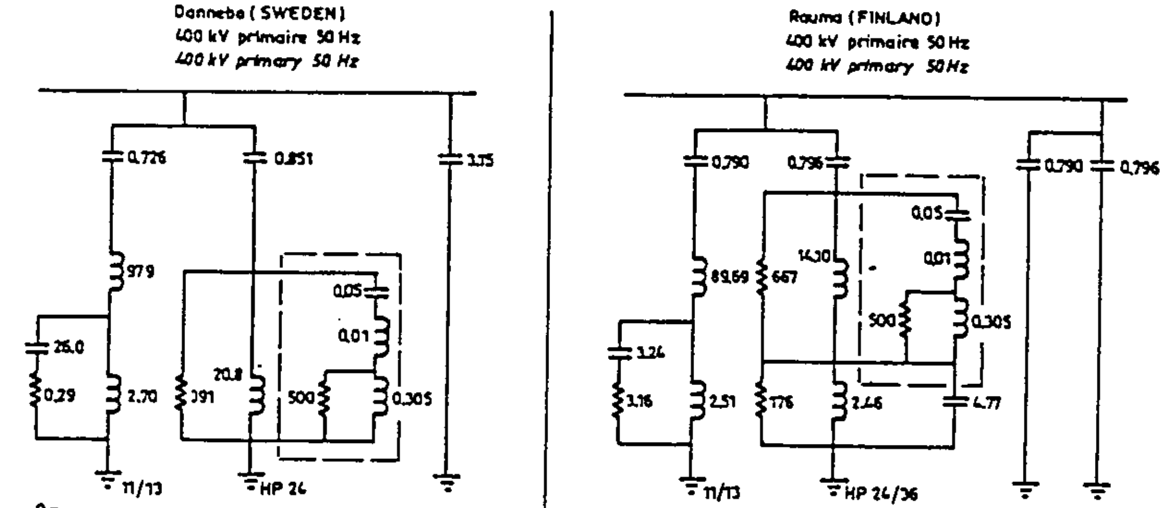
$$|Z_{max}|_n = n \cdot Z_{max}(50) \quad |Z_{min}|_n = \sqrt{n} \cdot Z_{min}(50)$$

Phase angle limits = 80°/0° for n = 2 to 4, 75°/-75° for n = 5 to 10, 70°/-70° for n = 11 to 50

These "base" sectors have been enlarged, when necessary, following the results of harmonic impedance calculations in different network conditions.

The initial studies for AC filter design were performed using the classical approach, i.e. the harmonic currents have been evaluated assuming negligible impedance for the AC system and infinite inductance for the smoothing reactor. The results have shown the need to install a 3rd harmonic filter in the station connected to the weakest AC network (Codrongianus, SCR of about 4 pu) ; in fact a 3rd harmonic voltage distortion 70 % higher than the specified limit (1 %) was found.

FENNO-SKAN



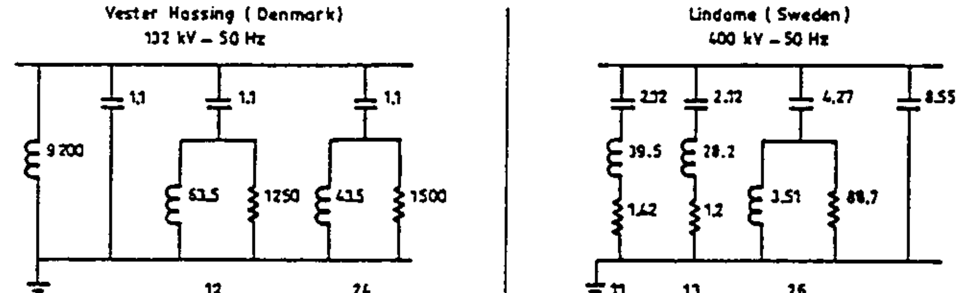
Danneba (SWEDEN):

	11/13	HP 24	
Q =			
F.R.P. =	36.7	42.9	158.3
N =	1	1	1

Rauma (FINLAND):

	11/13	HP 24/36	
Q =	97/85	73/49	
F.R.P. =	40.0	40.1	79.7
N =	2	2	1

KONTI-SKAN II



Vester Hassing (Denmark):

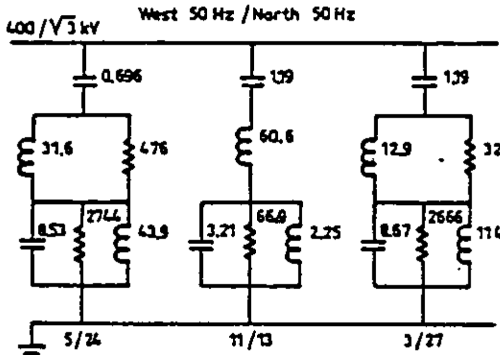
			12	24
Q =	–	–	5	4,6
F.R.P. =	55.4	55.3	55.3	20.1
N =	1	1	2	1

Lindome (Sweden):

	11	13	26	
Q =	65	65	3.1	–
F.R.P. =	11.6	11.6	23.3	46.8
N =	1	1	1	2

VINDHYACHAL (INDIA)

West 50 Hz / North 50 Hz



	5/24	11/13	3/27
Q =	200	200	200
F.R.P. =	35	60	60
N West =	2	2	2
N North =	2	2	2

Légende:

- (capacitor) valeur en µF – *value in µF*
- (inductor) valeur en mH – *value in mH*
- (resistor) valeur en Ω – *value in Ω*

F.R.P. = Puissance réactive fondamentale triphasée Mvar
Fundamental reactive power Mvar 3 phase

Q = Coefficient de qualité du filtre
Quality factor of the filter

N = Nombre de filtres de chaque type
Number of filters of the represented type

In order to check the real necessity for this 3rd harmonic filter, more detailed calculations were performed using a new approach which took into account the existing interactions between AC and DC sides for low order harmonics. The results showed a remarkably beneficial effect (3rd harmonic distortion within limits) of these interactions for Sacoi 2, allowing the installation of the 3rd harmonic filter to be avoided in this case.

Both converter stations are equipped with the second-order damped filter banks, one tuned at harmonic 12 (dealing with 11 and 13) and the other one tuned at 23 harmonic (dealing with 23, 25 and higher order harmonics). The total var generation at fundamental frequency is 95 Mvar and 76 Mvar for Codrongianus and Suvereto converter station respectively.

7.19 Fenno-Skan HVDC

The Fenno-Skan HVDC link interconnects the Finnish and the Swedish networks with a submarine cable across the Gulf of Bothnia. The rated power of the monopolar link is 500 MW (400 kV, 1250 A). At both sides the link is connected to 400 kV AC network. In parallel with the link there are two 400 kV AC lines in the north. The limit for the total rss voltage distortion in the AC network, Deff, is 1.0 %.

7.19.1 Finnish converter station : Rauma

There are two filters, 80 Mvar each, and an 80 Mvar shunt capacitor in order to compensate fully the reactive power consumption at rated load. The maximum size of the filters is dimensioned by the limit of the 3 % voltage change on switching. The filters are identical and consist of two branches, one double-tuned to 11/13 harmonic and another high-pass type, double-tuned to 24/36 harmonic. The shunt bank has been made suitable for future extension into a filter. Non-characteristic harmonics have been taken into account in the filter design by assuming resonance with the AC network at each harmonic.

7.19.2 Swedish converter station : Dannebo

There is an 80 Mvar filter with two branches : one branch double-tuned to 11/13 harmonic and another high-pass type branch tuned to 24th harmonic. The overall reactive power balance is achieved with a 160 Mvar shunt capacitor.

7.20 Konti-Skan 2

The Konti-Skan 2 HVDC link between Sweden and Denmark complements the existing Konti-Skan 1 transmission which has been in service since 1965. The link has a nominal rating of 300 MW at 282 kV and includes a 88 km underwater cable.

The Lindome station is equipped with one filter bank consisting of 11, 13 and high-pass 24 harmonic branches. In addition, two shunt capacitor banks are provided. The rating of the filter bank is such that the station can be operated with only the filter bank in the whole load range. The shunt capacitor banks are, however, necessary to meet the performance criteria at higher power levels.

The Vester Hassing filter scheme comprises three filter banks, all with damped characteristics, with cut-off frequencies at the 11, 13 and 24 harmonics. In addition, one shunt capacitor bank and one shunt reactor are provided for reactive compensation.

7.21 Vindhyachal

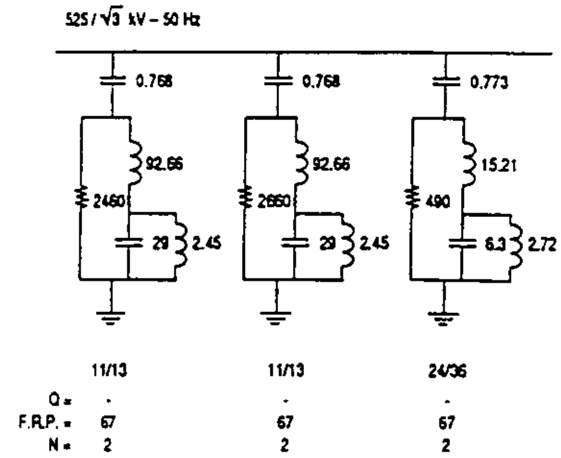
The Vindhyachal back-to-back HVDC scheme in India connects the Northern and Western power systems in the region of Rihand. The scheme consists of two 12-pulse 250 MW blocks. At both sides the link is connected to a 400 kV network. The AC filter performance limits are : Dn = 1 %, D = 4 % and TIF = 30.

In addition, if one or more generators are connected at either Vindhyachal West or Vindhyachal North, then at that converter Deff shall not exceed 3 %. The generator harmonic current shall not exceed 8 % continously, 30 % for more than 1 minute and 77 % for more than 10 secondes.

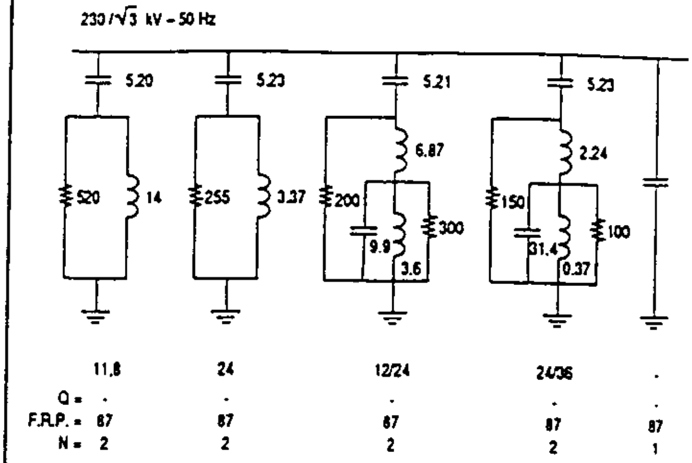
At harmonics (3 n + 1) and (3 n - 1) the arithmetic sum of maximum individual harmonic currents shall not exceed 1.5 % and no single harmonic current shall exceed 1 %.

A common AC filter design was adopted for both Northern and Western buses. Double tuned 11/13 filters are provided and double tuned branches at 3/27 and 5/24 are also installed. The filtering at 3rd harmonic is to eliminate resonances with the AC network, and at 5th to limit individual harmonic distortion. The above filters are arranged in two identical banks with each branch being individually switchable in order to satisfy reactive power requirements and performance criteria for operation with one filter out of service. Further reactive power compensation is enabled by the provision of a switched shunt reactor and a shunt capacitor. Reactive power control is mainly achieved by means of a very wide range of control angles and this had an important influence on the filter design.

Gezhouba (CHINA)

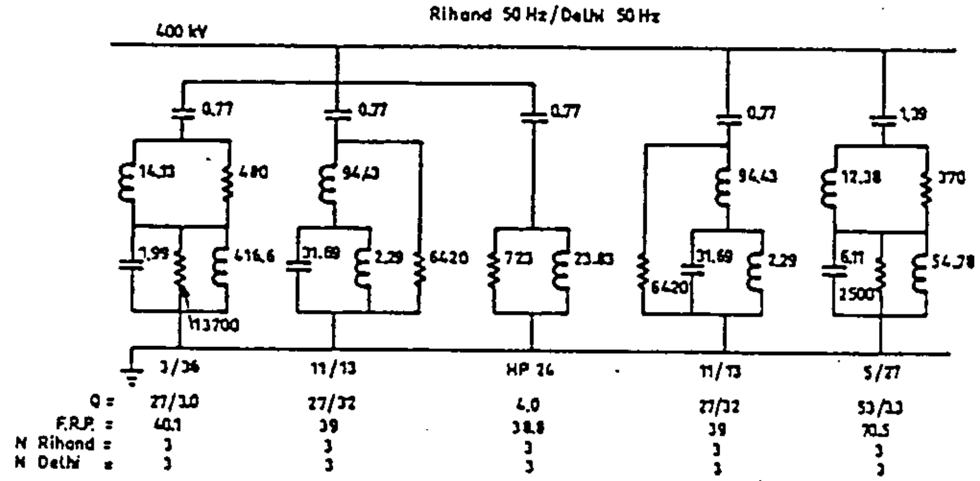


Nan Quiao (CHINA)



RIHAND – DELHI (INDIA)

Rihand 50 Hz/Delhi 50 Hz



Légende :

- ⊣⊢ valeur en μF – *value in μF*
- (inductance) valeur en mH – *value in mH*
- (résistance) valeur en Ω – *value in Ω*

F.R.P. = Puissance réactive fondamentale triphasée Mvar
Fundamental reactive power Mvar 3 phase

Q = Coefficient de qualité du filtre
Quality factor of the filter

N = Nombre de filtres de chaque type
Number of filters of the represented type

7.22 Gezhouba - Shanghai HVDC

The Gezhouba-Shanghai project is the first long distance HVDC transmission scheme to be commissioned in the Peoples Republic of China. The rated power of this ± 500 kV DC bipolar scheme is 1200 MW from Gezhouba (rectifier station) located in Central China to Nan-Qiao (inverter station) located in the Shanghai area. The Gezhouba converter station is connected to the 525 kV AC system near the Gezhouba Hydro power plant. The Nan Qiao converter station is connected to the 230 kV AC system near Shanghai.

At Gezhouba a total of six AC filter banks of the double-tuned high pass type are installed. Four of these filter banks are tuned to the 11/13 harmonic and two of them to the 24/36 harmonic. Each of the individual filter sub-banks is rated for 67 Mvar giving 402 Mvar installed for the whole converter station.

The 230 kV AC-filters at Nan Qiao are also split up into two identical branches per converter pole each comprising one high-pass filter 12, one high-pass filter 24, one double tuned high-pass filter 12/24 and one double tuned high-pass filter 24/36. In addition to these filter circuits one shunt capacitor bank is installed at the 230 kV bus.

Each of the individual filter banks and shunt capacitor banks is rated for 87 Mvar giving 783 Mvar installed for the whole converter station.

The chosen design fulfills the performance requirements specified at both converter stations as

D_n = 1.0 %, D(2-50) = 4.0 % and THFF = 1.0 %

Special design aspects were that state-of-the-art high-pass damped, double-tuned filter circuits were employed for extremely high AC voltage 525 kV and for 230 kV. The use of a reactive power and AC voltage control mode of the converters resulted in increased firing angles and increased harmonic currents throughout the range of converter operation, thus aggravating filter performance.

7.23 Rihand-Delhi

The Rihand-Delhi HVDC transmission in India connects the coal-fired generation of the Rihand region to the load centre of Delhi. The rated power of the bipolar link is 1500 MW and the transmission voltage 500 kV. At both sides the link is connected to a 400 kV network.

The AC filter performance criteria are defined as D_n = 1 %, D = 4 % and TIF = 30.

In addition, if one or more generators are connected at either Rihand or Delhi, then at that converter station Deff shall not exceed 3 %, the generator harmonic current shall not exceed 8 % continously, 30 % for more than 1 minute and 77 % for more than 10 secondes.

At harmonics (3n + 1) and (3n - 1) the arithmetic sum of maximum individual harmonic currents shall not exceed 1.5 % and no single harmonic current shall exceed 1 %.

A common AC filter design was adopted for both Rihand and Delhi stations, but with different grouping arrangements. Double-tuned 11/13 filters plus a high-pass damped filter with cut-off at the 24 harmonic, and double-tuned branches at 3/36 and 5/27 are provided. The filtering at the 3rd harmonic is to eliminate resonances with the AC network, at 5 to limit individual harmonic distortion and at 27 and 36 to limit TIF. The above filters are arranged in three identical banks. The individual branches are arranged in switchable groups in order to satisfy reactive power requirements and criteria for operation with one filter out of service.

7.24 McNeill

The McNeill 150 MW back-to-back converter station located in Alberta, Canada provides the first power connection between the western and eastern systems and enables a bi-directional exchange of energy and standby capacity between Alberta Power Limited and Saskatchewan Power System.

All of the reactive power compensation equipment, shunt reactors, shunt capacitors and harmonic filters, is connected to a 25 kV tertiary winding on the converter transformers. This approach provides an economic design of equipment which meets the design criteria to limit maximum reactive power change and steady state voltage change when switching reactors or capacitors. On the Alberta side there are three 27 Mvar capacitor banks, configured as harmonic filters, and two shunt reactors, rated at 25.5 Mvar and 17 Mvar. On the Saskatchewan side there are three 25.5 Mvar capacitor banks configured as harmonic filters, two 25.5 Mvar capacitor banks which have de-tuning reactors, and four shunt reactors, two of 25.5 Mvar, and one each of 17 Mvar and 8.5 Mvar. In addition a single 25.5 Mvar capacitor bank is switchable between either Alberta or Saskatchewan sides of the scheme, and is normally available to the rectifying station. Binary switching of capacitors and reactors is used to achieve the specified performance requirements.

The harmonic filters were designed to comply with the following performance limits : Dn = 1 %, D = 4 %, TIF = 35, IT = 4000

The most unfavourable conditions of ambient temperature, system frequency and manufacturing tolerance were assumed for all studies, in addition to resonance conditions between the filters and the AC supply systems.

The harmonic filters consist of two switched groups each comprising 11, 13, and 23 tuned arms, and a switched group comprising 11 and 13 tuned arms.

Each switched filter group has a rating of 27 Mvar on the Alberta side, and 25.5 Mvar on the Saskatchewan side. In order to avoid an anti-resonance condition between switched capacitor banks and the harmonic filters, and to limit switching transients, each switched capacitor banks is de-tuned to the 25th harmonic.

Studies of the magnification of low order harmonics from sources in the supply system indicated a potentially serious condition at 3rd and 5th harmonics on the Alberta side of the scheme. The provision of a 6 Mvar 3/5 double-tuned filter prevents this magnification of system harmonics. To avoid exceeding the limits on reactive power generation a 6 Mvar shunt reactor is also provided, the double-tuned filter and reactor being switched together.

8. SUMMARY AND CONCLUSION

8.1 In this paper the different sources of non-characteristic harmonics and their importance compared to characteristic harmonics have been examined, taking into account the possibility of resonance conditions involving the AC system and AC filters ; interaction with the DC side and the converter controls have also been considered.

8.2 The harmonic behaviour of converters operating under unbalanced conditions is fairly well known and digital tools are available for analysis.

8.3 Non-characteristic harmonics are generated mainly by a combination of following sources :

- unbalance of AC system voltage,
- unbalance of transformer reactances,
- unbalance of firing angles.

Of these three sources, the first two are the most important in schemes equipped with modern controls.

8.4 Data have been presented on some recent HVDC schemes , including many cases in which low order filters are used.

8.5 Low order filters are not always needed, even in case of low short-circuit ratio. None of the HVDC schemes reported need for specific harmonic for non-characteristic harmonics above 10.

8.6 In order to obtain economical filtering performance, it is essential for the user to specify correctly the expected unbalance of his AC system (1 % of negative phase sequence is a typical value). For the same reason it is of great importance to limit the maximum tolerances between transformer reactances. It is reasonable to use an expected value of unbalance (eg ± 1 % of nominal reactance) which is less than the guaranteed value (eg ± 5 %), when carrying out filter performance calculations.

8.7 The introduction of additional filters to limit low order harmonic resonance conditions increases both capital cost and losses. It is therefore very important to know as closely as possible how the impedance/frequency locus of the AC system varies as a function of operating conditions. Special emphasis should be placed on determining the resistive part of the system impedance which contributes to damping. Adequate damping given by the combination of the AC system and filters is important in some cases to reduce the amplitude of temporary overvoltages at that frequency for which the low order filter is designed. This may give advantages in any condition in which the transformers are over-excited e.g. in the case of load rejection following a severe AC system fault. This last effect may be determinant for the insulation coordination and for energy discharge duties of all related equipment at the converter station.

8.8 Much more information need to be collected about system damping, especially by the way of field measurements. Utilities must play a major role in this difficult task.

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APPENDIX 1

SENSIVITY ANALYSIS OF NON-CHARACTERISTIC HARMONIC CURRENTS GENERATED BY UNBALANCES IN AC/DC CONVERTERS

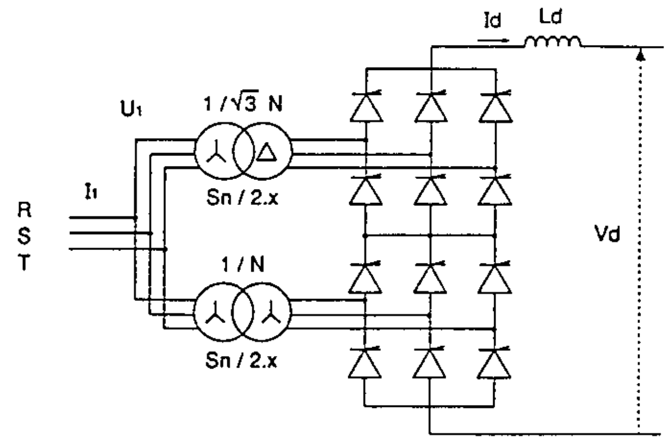
It is inevitable that AC/DC converter equipment will be subjected to unbalances in practical operation and will inherently contain some asymmetrical parameters due to manufacturing tolerances. In order to assess the significance of these various factors of asymmetry, Working Group 14.03 postulated a typical 12-pulse convertor configuration and examined the consequences of imposing different types of unbalance, one at the time. Figure 4 shows the configuration and definitions and Table 1 lists the general assumptions and cases studied. The aim of this calculation is to clarify the relative importance of each unbalance source for practical values and to evaluate their sensitivity. In reality the result of unbalances is a combination of each effect, which can increase or decrease some harmonics. One must note that an adverse harmonic effect can also appear due to frequency changing (50/60 Hz or 50/50 Hz with different frequency controls).

Case 1	Unbalance of the AC supply voltage : ΔU R = S = 100 % T = 99 %
Case 2	Unbalance of transformer leakage reactances in one phase : ΔX 5 phases = 20 % 1 phase star-delta = 21 %
Case 3	Unbalance of transformer leakage reactances between bridges : $\Delta' X$ 3 phases star-star = 20 % 3 phases star-delta = 21 %
Case 4	Unbalance of transformer turn-ratios : ΔN star-star = 100.0 % star-delta = 100.5 %
Case 5	Unbalance of firing angles : $\Delta\alpha$ 5 valves = 15 ° valve 1 = 15.2 °

Table 1 : Study Cases

1. GENERAL ASSUMPTIONS

Figure 4 shows the system which was studied and the nomenclature adopted. The AC system supplying the convertor was assumed to have a negligible impedance at any frequency, i.e. the voltage at the terminals of the convertor has a sinusoidal waveform at the fundamental frequency. The various types of unbalance were examined one at the time.



α = firing angle
$1/N$ = turn-ratio
x = leakage reactance (per unit)
Sn = transformer power = $\sqrt{3}\ U_{1n} I_{1n}$
I_1 = fundamental current
U_1 = fundamental voltage
Id = direct current
Vd = direct voltage
$Id = \pi / 2\sqrt{6}\ N\ I_1$
$Vd = 2\,(3\sqrt{2} / \pi\, U_1 \cos\alpha - x / \sqrt{2}\ NU_{1n} I_1 / I_{1n})$

Assumptions for calculation
$\alpha = 15°$, $N = 1$, $x = 20\ \%$, $Ld = \infty$
$\gamma = 15°$, U_{1n} , $I_1 = I_{1n}$

Figure 4 : Converter scheme used for senstivity analysis

2. CALCULATION

Table 2 gives a detailed listing of all harmonics up to 50th resulting from each of these individual sources of harmonics. [It is of interest to record that the effects of phase reactance unbalance and firing angle unbalance are different for the two types of converter transformer. The results are more severe for the star-star transformer, which does not have a delta winding, and these results are given in the Table. Results are also presented in the charts of figure 5.

3. CONCLUSIONS

The main conclusions are that system unbalance produces only triplen order harmonics. Errors in turn-ratios and reactances between the two transformers produce residual harmonics associated with a 6-pulse converter. Asymmetry of the phase reactances of a transformer produces harmonic currents of all odd orders. Errors in firing angles produce harmonics of all orders, both odd and even, but for practical values of firing angle error this source of unbalance produces smaller values of odd order non-characteristic harmonic currents than practical values of the other sources of unbalance. Difference of transformer reactance between bridges predominates for non-triplen harmonics and differences in single phase reactances can be equally significant for triplen harmonics.

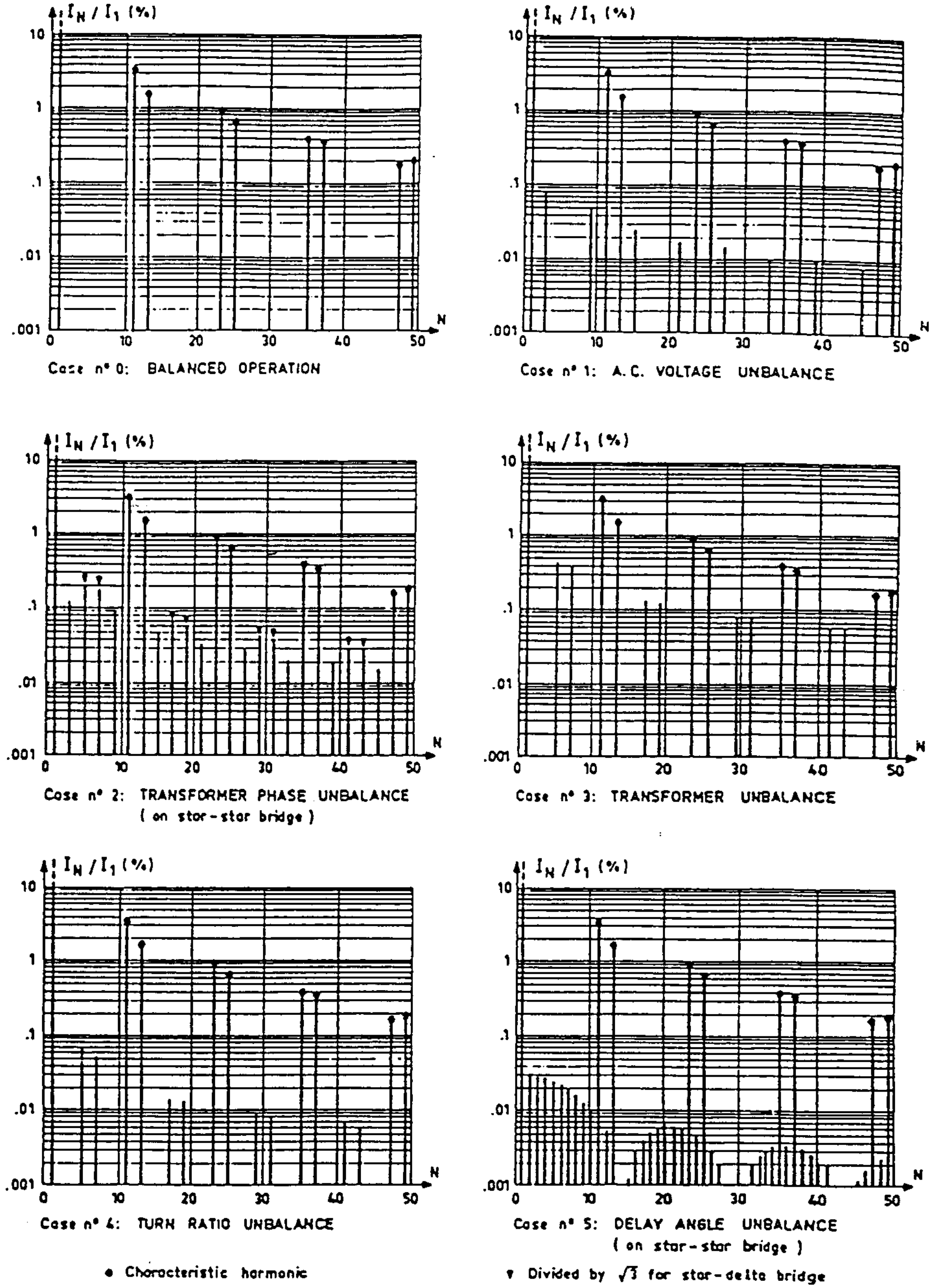


Figure 5 : Typical 12 pulse converter current spectra for different unbalance sources.

Harmonic order	Reference Ideal balanced convertor	Case 1 ac voltage unbalance	Case 2 transf. phase unbalance	Case 3 transf. unbalance	Case 4 turn-ratio unbalance	Case 5 delay angle unbalance
1	100.0	100.0	100.0	100.0	100.0	100.0
2						0.0279
3		0.069	0.130			0.0268
4						0.0253
5			0.208	0.414	0.0666	0.0234
6						0.0213
7			0.184	0.366	0.0516	0.0189
8						0.0163
9		0.043	0.0904			0.0136
10						0.0109
11	3.09	3.10	3.08	2.94	3.08	3.09
12						0.0056
13	1.49	1.50	1.49	1.39	1.49	1.49
14						0.0009
15		0.0225	0.0472			0.0011
16						0.0028
17			0.0683	0.135	0.0133	0.0041
18						0.0032
19			0.0617	0.122	0.0172	0.0058
20						0.0062
21		0.0136	0.0339			0.0062
22						0.0060
23	0.842	0.851	0.848	0.801	0.843	0.845
24						0.0048
25	0.597	0.602	0.596	0.542	0.596	0.598
26						0.0030
27		0.0134	0.0274			0.0019
28						0.0009
29			0.0426	0.0832	0.0087	0.0001
30						0.0011
31			0.0387	0.0757	0.0077	0.0019
32						0.0026
33		0.0094	0.0210			0.0031
34						0.0035
35	0.363	0.370	0.372	0.354	0.362	0.364
36						0.0037
37	0.328	0.334	0.332	0.304	0.328	0.330
38						0.0032
39		0.0091	0.0190			0.0027
40						0.0022
41			0.0309	0.0601	0.0065	0.0015
42						0.0009
43			0.0288	0.0558	0.0059	0.0002
44						0.0005
45		0.0070	0.0155			0.0011
46						0.0016
47	0.161	0.166	0.170	0.166	0.161	0.161
48						0.0024
49	0.181	0.187	0.185	0.175	0.182	0.182
50						0.0026

Table 2 : Harmonic currents generated by each unbalance source
(% of fundamental current)

APPENDIX 2

INTERACTIONS BETWEEN AC AND DC SYSTEMS

Unbalances in the AC network, or within the converter transformer, create non-characteristic harmonics of direct voltage as well as of alternating current. These DC-side voltages will cause ripple on the direct current, according to the admittance of the overall DC network. Rapid control action, as is typically used in HVDC current regulators, will cause a coherent modulation of firing angle in direct response to the ripple on direct current. The overall effect is a closed-loop response, which is sensitive to the following factors :

a) DC-side admittance at the harmonic of interest. This admittance includes the effects of smoothing reactors, DC filters, DC line, converter transformers, and the AC system at the remote DC converter stations.

b) Idc-regulator response at the harmonic of interest. This is important whether the Idc control is implemented at the local or the remote converter station.

c) Local AC-side impedance at the harmonics of interest.

A more detailed explanation of this interaction is provided in [3.1].

The most likely situation where this interaction may be important is with AC voltage unbalance. Such unbalance creates a second-harmonic ripple on the dc-side, and a third-harmonic AC-side current. Thus, the admittance of the DC system at second harmonic is important, as is the impedance of the AC systems at third harmonic. The AC-side impedance to negative-sequence, fundamental-frequency components must also be known.

An example taken from [3.1] provides an indication of the relative importance of considering such an interaction in system design. This example involves a typical converter supplied by an AC system having an SCR of 3 pu. A second-harmonic filter is assumed to be connected on the DC side of the smoothing reactor, thereby decoupling the response from the DC line and other terminals.

Figure 6 illustrates the simple system. Figure 7 illustrates waveshapes associated with applying a negative-sequence AC voltage unbalance of 2 % at time zero. Note the substantial second-harmonic ripple on the direct current and regulator output, and severe 3rd harmonic distortion on the AC voltage.

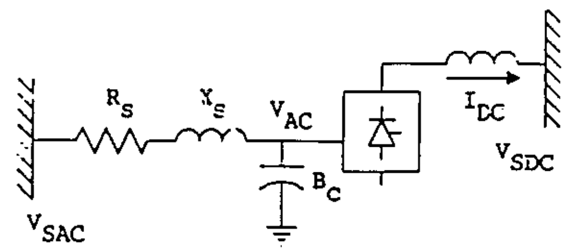


Figure 6 : system example case

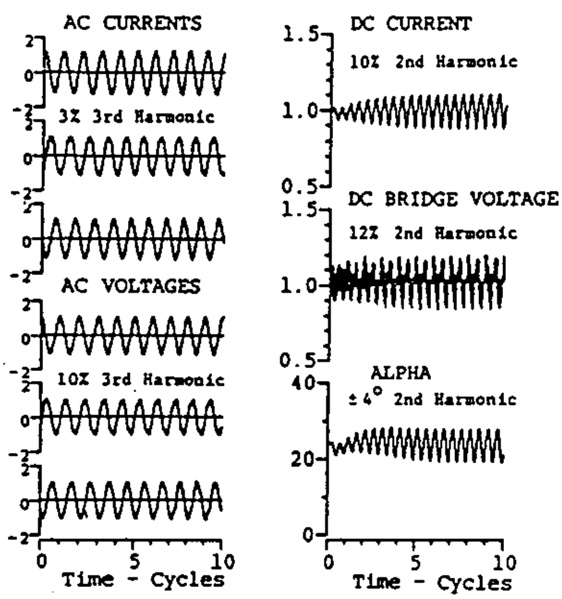


Figure 7 : Example of High Steady State distortion due to a 2 % voltage unbalance.

Figure 8 illustrates the importance of including the interaction in this system. This figure shows the sensitivity of third-harmonic AC voltage distortion as a function of shunt capacitance, for three different assumptions of the DC-side response (a negative-sequence voltage of 2 % is assumed to be driving the system).

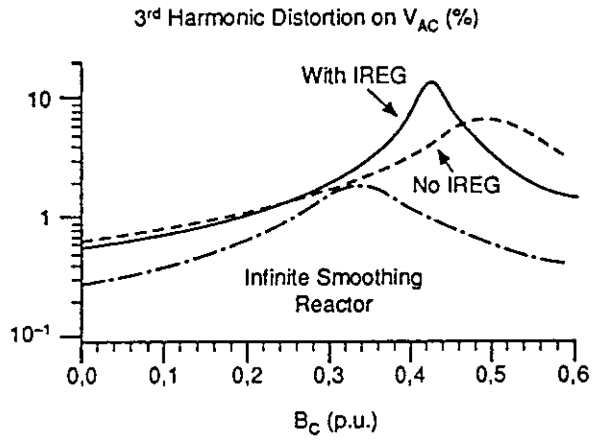


Figure 8 : Impact of 2 % negative-sequence AC voltage unbalance versus shunt AC capacitance for the example case of figure 6.

The lowest levels of distortion occur when the interaction is neglected, as shown by the curve labeled as "Infinite Smoothing Reactor". Note that the peak on this curve, of approximately 2 % distortion, occurs when the shunt capacitance resonates with the source impedance at third harmonic.

When a finite smoothing reactor is used and the current regulator response is included, the resonance occurs with a different value of shunt capacitance (solid curve, labeled 'with IREG'), and the maximum distortion increases to over 10 %. Removing the current regulator shifts the resonance to an even higher level of shunt capacitance, decreasing the peak distortion to below 10 % but making the situation worse for levels of shunt capacitance above 0.47 pu (dashed curve labeled 'No IREG').

Incorporating this type of interaction in HVDC system design can be quite difficult in practice, due to the necessity of knowing the DC-side design at an early stage. Nonetheless, such interactions should be considered at least in the rating of equipment.

There will be some impact on telephone interference as well as on low-order harmonic distortion, particularly due to 15 and 27 harmonics on the AC side. One means of dealing with this possibility is to increase the level of these harmonics assumed in the design stage, to account for a maximum expected DC-side current ripple at second harmonic.

APPENDIX 3

DEFINITIONS USED FOR AC HARMONICS

The criteria used depend primarily on the nature of harmonic disturbances which are likely to occur.

1. For equipment sensitive to the presence of just one harmonic, an individual maximum level criterion should be used :

1.1. Maximum individual harmonic voltage level :

$$Dn = \frac{Un}{U1}$$

1.2. Maximum individual harmonic current level :

$$D'n = \frac{In}{I1}$$

Subscript 1 refers to rated fundamental and subscript n to the harmonic considered.

2. For equipment sensitive to the additional power dissipated by a range of harmonics, the root-sum-square (rss) quadratic summation should preferably be used.

2.1. Voltage distortion :

RSS distortion =

$$= Deff = \frac{1}{U1}\sqrt{\sum_{n=2}^{m} Un^2}$$

2.2. Current distortion :

$$D'eff = \frac{1}{I1}\sqrt{\sum_{n=2}^{m} In^2}$$

3. In some cases the theoretical maximum deviation, i.e. the arithmetic sum of the harmonics as a ratio of the rated fundamental, is specified :

3.1. Maximum voltage deviation :

$$\text{Arithmetic distortion} = D = \frac{1}{U_1}\sum_{n=2}^{m} Un$$

3.2. Maximum current deviation :

$$D' = \frac{1}{I1}\sum_{n=2}^{m} In$$

For practical reasons this summation is generally limited to m = 50.

4. With respect to telephone interference, there are two systems of weighting that take into account the response of the telephone equipment and the sensitivity of the human ear :

4.1. The Telephone Interference Factor (TIF) in the Edison Electric Institute - Bell Telephone System :

$$TIF = \frac{1}{U}\sqrt{\sum_{n=1}^{m} (k_f * p_f * U_f)^2}$$

U represents the r.m.s. voltage of the transmission line and Uf the harmonic voltage of frequency f and of order n, kf the coupling coefficient (equal by definition to 5f), pf the weight of the harmonic of frequency f which has a maximum equal to 1 for f = 1000 Hz.

4.2. The Telephone Harmonic Form Factor (THFF in the CCITT system), which is defined like the TIF, with the difference that kf is equal by definition to f/800.

An approximate relation, because pf factors are nearly identical in both systems is :

$$\frac{TIF}{THFF} = 4000$$

5. Longitudinal or transverse induced voltages on the telephone line are expressed by the root-sum-square combination of induced harmonic voltage (pf are the same as for TIF or THFF) :

$$Un = \sqrt{\sum_{n=1}^{m} (p_f * U_f)^2}$$

6. The currents in the power transmission line are represented by a single current obtained by weighting each harmonic current with the corresponding factor of the system used :

6.1. IT product, in the E.E.I.- B.T.S. system :

$$IT = \sqrt{\sum_{n=1}^{m} (k_f * p_f * I_f)^2}$$

If = r.m.s. current of frequency f expressed in Amperes.

6.2. Equivalent disturbing current (Ipe) : identically defined in the C.C.I.T.T. system.

APPENDIX 4

THE EFFECT OF INCLUDING NON-CHARACTERISTIC HARMONICS INTO PERFORMANCE CALCULATIONS

The presence of non-characteristic harmonics can have a major influence on the result of performance calculations when using some of the design criteria in common use.

Table 3 shows a typical voltage harmonic spectrum up to the 85th harmonic calculated for an HVDC scheme with tuned 11th and 13th filters and damped high pass filters for higher harmonics. Typical unbalance effects were included as listed in Table 4. For each harmonic the network was tuned to the worst value with a minimum resistance defined. A current spectrum (not listed) was derived for the calculation of IT product. Table 5 shows how the results of the calculated performance depend on the choice of harmonics which are taken into account.

The conclusion which can be drawn are :

- for total distortion, the lowest harmonics are the most important,

- the calculation of TIF and IT product will be reasonably accurate even if only characteristic harmonics up to order 50 and non-characteristic harmonic up to order 10 are taken into account,

- provided that a damped high pass filter is included for harmonics above order 23, non-characteristic harmonics above order 20 only influence the results for arithmetic distortion.

The arithmetic distortion does not bear any correlation to actual performance in real schemes. Because arithmetic distortion does not converge as more harmonic orders are included, this criterion can lead to uneconomical design of filter, without any benefit for other performance criteria.

The rss based distortion factor is the more relevant criterion for the severity of total harmonic because it corresponds physically to the total power of harmonics.

order	/Uh(%)	order	/Uh(%)	order	/Uh(%)	Order	/Uh(%)	Order	/Uh(%)	Order	/Uh(%)	Order	/Uh(%)
1	100	13	0.14	25	0.090	37	0.044	49	0.055	61	0.056	73	0.047
2	0.14	14	0.0032	26	0.0006	38	0.0004	50	0.0006	62	0.0007	74	0.0008
3	0.89	15	0.12	27	0.010	39	0.0006	51	0.010	63	0.012	75	0.012
4	0.056	16	0.0092	28	0.0008	40	0.0004	52	0.0007	64	0.0008	76	0.0007
5	0.49	17	0.057	29	0.0063	41	0.0034	53	0.0052	65	0.0060	77	0.0061
6	0.081	18	0.0075	30	0.0011	42	0.0006	54	0.0010	66	0.0010	78	0.0011
7	0.37	19	0.028	31	0.0053	43	0.0037	55	0.0053	67	0.0058	79	0.0060
8	0.033	20	0.0024	32	0.0006	44	0.0005	56	0.0007	68	0.0007	80	0.0007
9	0.39	21	0.024	33	0.0079	45	0.0075	57	0.011	69	0.012	81	0.012
10	0.011	22	0.0009	34	0.0005	46	0.0005	58	0.0008	70	0.0007	82	0.0007
11	0.25	23	0.13	35	0.052	47	0.054	59	0.057	71	0.051	83	0.041
12	0.0068	24	0.0006	36	0.0004	48	0.0008	60	0.0010	72	0.0010	84	0.0010
												85	0.040

Table 3 : Typical voltage harmonic spectrum

No-load ideal direct voltage	273.3 kV
Nominal direct current	1.6 kA
Nominal relative inductive voltage drop	6.3 %
AC network impedance phase angle - 3rd harmonic - all other harmonics	 80.0° 85.0°
Equivalent frequency deviation	1.3 %
Negative sequence voltage	1.0 %
Standard deviation of firing angle variation	0.022°
Maximum variation of dx from nominal	+/- 2.0 %

Table 4 : Main circuit data and unbalance effects used

Case	Harmonics taken into account		Results			
	Charac-teristic	non-charac teristic	arith dist	rss dist	TIF	IT
				%	%	kA
a	none	≤10	2.46	1.16	5.6	86
b	≤20	≤20	3.08	1.20	11.7	495
c	≤50	none	0.82	0.34	16.0	534
d	≤50	≤10	3.28	1.21	16.8	541
e	≤50	≤20	3.51	1.22	18.0	542
f	≤50	≤50	3.59	1.22	18.1	544
g	≤85	none	1.11	0.36	17.0	537
f	≤85	≤10	3.57	1.21	17.8	544
i	≤85	≤20	3.80	1.22	19.0	545
j	≤85	≤85	4.00	1.22	19.1	547

Table 5 : Distortion performance versus harmonics taken into account

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