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BACK-TO-BACK HVDC SYSTEM PERFORMANCE WITH DIFFERENT SMOOTHING REACTORS

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ABSTRACT

The function of the dc smoothing reactor in a back-to-back dc system is addressed and the impact of the dc system performance is evaluated for sensitivity to variation of the size of the dc reactor. Through the use of a dc simulator, results are used to illustrate the effects on several performance indices, among these the inverter valve recovery voltage distortion, bypass pair formation and commutation failure, and ac and dc harmonics. Information is presented which may lead to the reduction in size of reactors currently supplied and expedite the ultimate elimination of the necessity for the reactor. Specific results indicated that only a relatively small dc reactor is required to significantly reduce voltage distortion, surge current, and ac and dc harmonics.

INTRODUCTION

The two distinct types of hvdc systems being constructed are (1) transmission systems incorporating either overhead lines or underground cable or a combination of both and (2) back-to-back asynchronous ties (See Figure 1). The latter type eliminates the line and/or cable and some of the dc equipment such as the dc filters. However, one element unique to hvdc systems which is common to both types is the dc smoothing reactor.

"Classical considerations" in literature regarding the functions of the dc smoothing reactor include the following:

(1) To prevent consequent commutation failures in the inverter by limiting the rate of increase of direct current during commutation in one bridge when the direct voltage of another bridge collapses.

(2) To decrease the incidence of commutation failures in the inverter during dips in alternating voltage.

(3) To decrease harmonic voltages and currents in the dc line.

(4) To smooth the ripple in the direct current sufficiently to prevent the current from becoming discontinuous or almost so at light loads.

(5) To limit current in the bypass valves or bypass pair due to discharge of the shunt capacitances of the dc line and terminal equipment in the event that all the bypass valves or pairs on one pole are fired simultaneously.

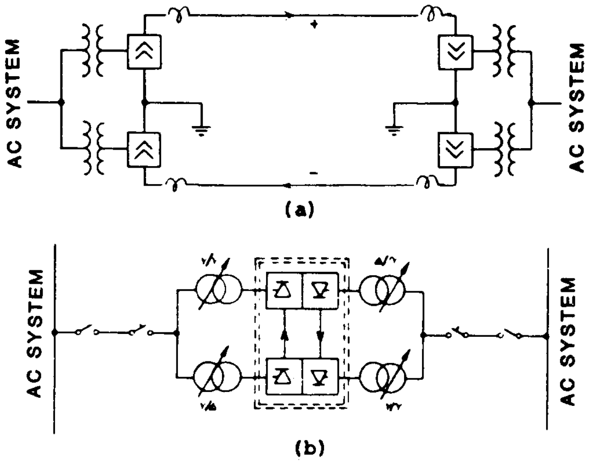

FIG. 1. Types of hvdc systems:
(a) transmission incorporating either overhead lines or underground cables or a combination of both,
(b) back-to-back asynchronous tie.

(6) To limit the crest current in the rectifier due to a short circuit on the dc line.

(7) To prevent resonance of the dc circuit at the power frequency.

Though the presence of the dc smoothing reactor is an essential part of the hvdc power transfer process in either type of system, the specific size of the reactor for a system does not appear to be all that critical from the indications of the wide spread of values used on existing systems. For transmission systems, reactor values from 0.27 to 1.5 H have been used as listed in Reference 2 while for back-to-back systems values vary from a high of 200 mH to a low of 12 mH. In fact, from claims made some systems are able to operate without an actual reactor under unusual conditions. How can this be and what evaluation process must be made to determine the feasibility of such operation? This paper serves to address this specific area regarding critical factors influencing the decision for back-to-back systems.

In addition, for thyristor schemes there exist intermediate reactors within the valves which contribute to the overall reactor function. Function No. 6, the limitation of dc line short-circuit currents to prevent valve damage, is normally the decisive factor. The valve reactors, however, make no contribution to this function as they are normally saturated due to the

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current levels involved. In back-to-back systems, the reactor size takes a more significant posture due to the lack of the inherent peak reducing effect on the dc-side short-circuit currents resulting from the line reactance with transmission systems. On the surface, this alone does not account for the significant difference in magnitude of reactor sizes for the two different system types.

DISCUSSION

Established System Designs

No precise or consistent methodology or complete body of knowledge exists in literature for sizing or even locating the reactor in a back-to-back system. Various options for location have been employed to date as illustrated in Figure 2. These include the following:

(A) Reactor in high-voltage side of dc loop with loop ungrounded.

(B) Reactor in low-voltage side of dc loop with loop grounded at midpoint of reactor.

(C) Reactor in high-voltage side of dc loop with low-voltage side grounded.

(D) Reactor in both sides of dc loop with loop grounded at midpoint of 12-pulse bridge.

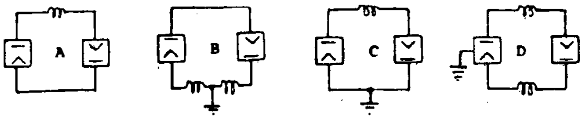

FIG. 2. Various dc smoothing reactor location options in back-to-back schemes.

Considerations employed in determination of the location of the reactor in the circuit include

(i) Insulation level of the equipment especially the reactor(s), e.g., insulation levels for reactors in "C" position have been only as low as 3.05 per unit of dc system voltage whereas in position "B" a level as low as 1.07 p.u. has been supplied (See Table IV in the Appendix).

(ii) Physical size of the reactor(s), oil vs. air, indoor vs. outdoor.

(iii) Whether reactor is switchable into and out of the circuit.

(iv) Cost of a spare and time for replacement in event of a failure.

Of the classical considerations, Nos. 3 and 5 are of course not applicable to back-to-back systems having no transmission line. Reviewing the literature published on some of the existing projects, one uncovers that in each case one or more of the remaining considerations were identified as the reason(s) behind the inclusion of the dc smoothing reactor. However, little material is presented on the determination of the optimum or actual size of reactor selected. A much used but over-simplified criterion for the functionality of smoothing reactor, i.e. acceptable performance of the reactor, is the so-called S_i-factor[1,2] as follows:

$$S_i = \frac{U_d}{L \times I_{dN}} \qquad [1]$$

where U_d = rated dc voltage in kV,
I_{dN} = rated direct current in kA
L = the dc circuit inductance in mH.

For a back-to-back system

$L = 3.5\ L_t + L_d$ where
L_t = converter transformer inductance
L_d = smoothing reactor inductance
when valve stray inductance is neglected.

Table I lists the majority of the recent back-to-back systems installed throughout the world with their respective dc reactor sizes given in millihenries. It is apparent from the table that reactor sizes have ranged from a low of 12mH to a high of 200 mH. In addition are listed the system dc voltage and current ratings applicable to each project. Also given in the table are the corresponding S_i-factors calculated for each project. For these calculations, L was assumed equal to simply L_d as was done in Reference [2]. The S_i-factors range in magnitude from 0.24 to 1.3 ms^{-1}. S_i was computed for each project in the case of an earth fault on the dc bus adjacent to the reactor but opposite the rectifier. A high value of smoothing reactor inductance corresponds thus to a low rate-of-rise of the short-circuit current. However, use of S_i-factor alone would result in a reactor size determined by only one (No. 6) of the considerations for reactor sizing. The final reactor size is a matter of optimization with respect to several considerations such as

(1) current extinction,
(2) commutation performance,
(3) harmonic current reduction,
(4) cost and available sizes in the market, e.g., the cost from one manufacturer for a 50 mH, 2000 A air-core reactor would be approximately 3.6 times the cost of a 10 mh reactor; and
(5) surge current suppression, among others.

This explains the wide range of reactor sizes used as indicated in Table I. The discussion in the following sections will address in greater detail how these other considerations affect the performance of the system and will demonstrate with examples how varying the

TABLE I

DC Project	Rated System DC Voltage	Rated System DC Current	DC Reactor Size	S_i	Location of Reactor	Min. Operating Current Level
Eddy County	82 kV	2495 A	70 mH	0.44 ms^{-1}	C	10%
Chateauguay	140.6 kV	3600	$4-9^{+}$	0.95	B	10
Acaray	25.6 kV	1950	2-13	0.42	B	20
Duernrohr	145kV	3790	85	0.42	C	10
Broken Hill	±4.16 kV	2400			A	<0
Highgate	56 kV	3600	12	0.9	A	20*
Blackwater	57 kV	3600	2-20**	0.35-0.62	C	20/10**
Eel River	80 kV	2000	100	0.38	C	10
Tri-state	50 kV	2000	60	0.38	C	15
Oklaunion	82 kV	2495	2-70***	0.23-0.44	C	10/5***
Madawaska	130.5 kV	2700	2-50	0.46	C	10
Miles City	82 kV	2495	74	0.41	C	10
Vyborg	±85 kV	2100	2-100	0.39	D	
Shin Shinanao	125 kV	1200	200	0.51	C	10
Uruguaina Tie	17.9 kV	3000	20	0.24	C	10
Sydney	50 kV	4140	2-15	0.34	B	10
Vindhyachal	69.7 kV	3600			C	

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* Can operate down to 10% current event without reactor but limiting minimal current without reactor to 20%. Has actually been operated without any reactor.

** Either of which reactor can be bypassed.

*** With one reactor in, can operate down to 10% dc current; with two reactors, can operate down to 5% dc current.

size of the reactor will change the performance on one or more parameters or performance outputs.

The table gives the minimum dc current for which each system is permitted to operate without concern, or simply the possibility of entering an unknown "gray" area of performance. A minimum current limit is introduced into the control system of the converter for the prevention, therefore, of discontinuous or intermittent direct current and should be set at about twice the critical current below which there is no overlap.[3] In most of the systems, as illustrated in the listing in the table, this level has been set at 10% of rated direct current. A few of the systems have been permitted under unusual circumstances to operate without a minimum current limit, i.e. a limit of 0%, as also indicated in the table by careful evaluation of system performance under these circumstances using simulator studies. This will be illustrated in the following sections of the paper.

One such evaluation applies to consideration of the ripple current normally present on the dc side. The average value of this ripple current[4] is given by the equation

$$I_d = \frac{V_{do}}{L_d}(0.0931 \sin \alpha)$$

where V_{do} = ideal no-load direct voltage. From this equation, it is obvious that the ripple current is inversely proportional to the reactor size. 12-pulse operation gives less ripple and consequently less margin is needed than with 6-pulse operation. The equation is then simplified to

$$I_d = \frac{V_{do}}{L_d}(0.023 \sin \alpha). \qquad [2]$$

In the following sections, information is presented on comparative performance for smoothing reactors of varying sizes including 0 mH. Conditions examined include inverter valve recovery voltage distortion, bypass pair formation, commutation failures, and dc and ac side harmonics.

Inverter Valve Recovery Voltage Distortion

An inverter valve requires a negative volt-second area following current commutation to the next valve. Inverters typically operate with a margin angle or extinction angle control system in order to maintain this positive voltage. In a 6-pulse bridge the valve voltage waveshape in Figure 3a clearly shows this margin angle, commonly indicated as γ.

The valve voltage waveshape of a 12-pulse bridge is more complex, as indicated in Figure 3b. For this example, there is an infinite smoothing reactor but the transformer commutating reactance contains a component common to both 6-pulse bridges.[5] Additional "dents", D' and D", are caused by commutations in the opposite valve in the other 6-pulse bridge. (For Valve 1 of the wye-wye bridge, distortions are caused by commutations of Valve 4 of the wye-delta bridge.) A concern is that the first positive-going dent indicated as D', can reduce the commutation margin. If the common impedance component is small, then the extra dents likewise will be small in magnitude.

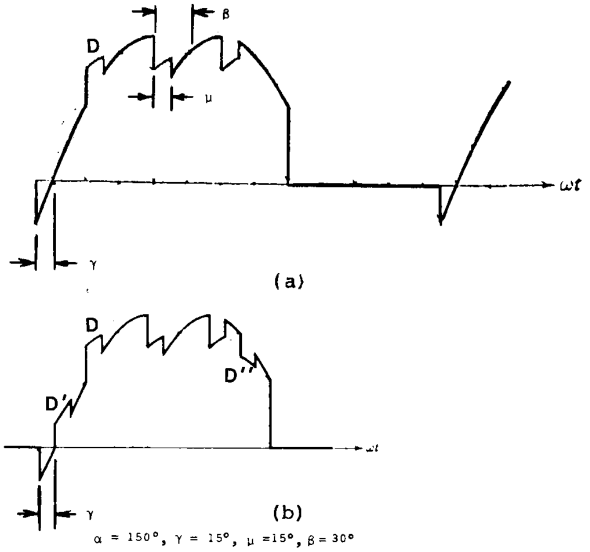

FIG. 3. Inverter valve recovery voltage:
(a) Dent D for three-phase 6-pulse bridge inverter,
(b) Additional dents D' and D" for three-phase 12-pulse two-bridge inverter due to common reactance.

Current ripple will affect the voltage waveshapes. In an asynchronous dc link the magnitude of the current ripple varies as the two networks "slip" with respect to each other. An implication of this discussion under the most adverse conditions would be a doubling of the harmonics as given in Equation [2]. Does that mean an increase in the size of the reactor derived by the conventional theory in current textbooks which ignores the other terminal or assumes only perfect dc with no harmonics from the other terminal? This is an unanswered question which the authors pose and leave for further study. A very large smoothing reactor can minimize this effect, but this is not an economic solution. Commutation overshoots, likewise will affect valve voltages. All these effects become more pronounced for weak system applications of back-to-back links, where ac bus voltages can become distorted.

Figure 4(a) is a simulator waveshape of inverter valve recovery voltage for a 200 MW system. There is one percent mutual commutating reactance, and a 12 mH smoothing reactor is used. The system is operating at rated current with nominal γ = 19 degrees. The positive-going notch is clearly visible, as is the reduction in negative volt-seconds. The measured margin angle is 14 degrees, but achieving this value requires the nominal margin angle setting to be a few degrees higher than the typical nominal range of 16-17 degrees. This has implications for both reactive power requirements and for valve design.

Figure 4(b) displays the inverter valve recovery voltage for the case with no smoothing reactor. The measured margin angle

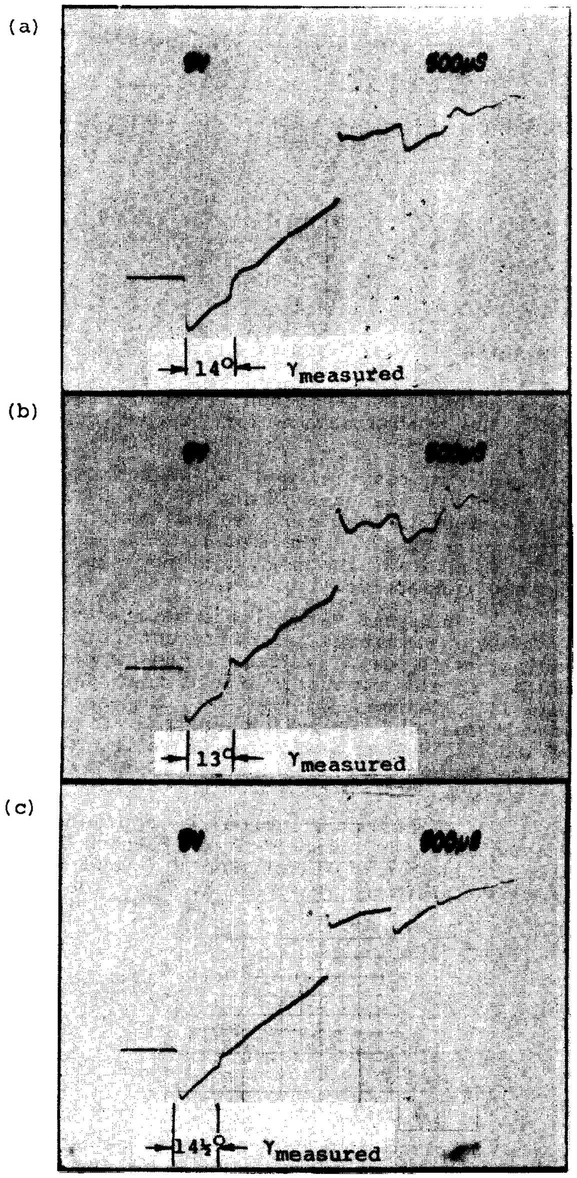

FIG. 4. Inverter valve recovery voltage with mutual commutating reactance for 12-pulse two-bridge. nominal setting = 19°.
(a) L_d = 12 mH.
(b) L_d = 0 mH.
(c) L_d = 36 mH.

is now 13 degrees, and there is considerable distortion in the waveshape. By comparison, Figure 4(c) illustrates the recovery voltage when a smoothing reactor of 36 mH is used. Only a minor reduction in volt-seconds is observed. In this system, a 12 mH reactor is seen to be adequate along with a small increase in nominal γ.

Bypass Pair Formation and Commutation Failures

An important function of the smoothing reactor as previously mentioned is to limit direct current for the rate of rise of direct current for inverter bypassing and commutation failures. Commutation reactance in the rectifier converter transformer will assist in limiting the peak current, but valve reactors will not as they will be saturated at this time.

Figures 5(a), (b) and (c) illustrate the direct current following the formation of inverter bypass pairs for differing smoothing reactor sizes. In Figure 5(a), when employing a smoothing reactor of 12 mH a peak direct current of 2.4 p.u. is observed with an oscillation in the vicinity of 60 Hz. As this would reflect to the ac side as 120 Hz, it is important to know the resonance points of the ac system.

Decreasing the smoothing reactor to 0 mH (Fig. 5(b)) results in a current peak of 3.6 p.u. and an oscillation of 200 Hz.

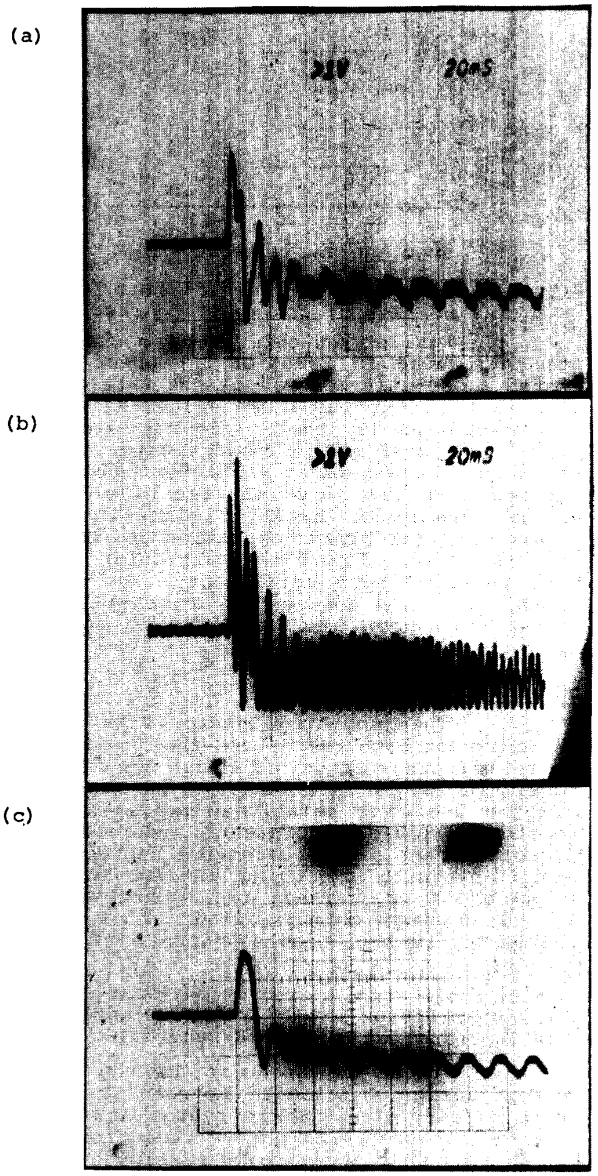

FIG. 5. Inverter bypass pair current,
(a) L_d = 12 mH.
(b) L_d = 0 mH.
(c) L_d = 36 mH.

Increasing the smoothing reactor to 36 mH (Fig. 5(c)) results in a current peak of 2.0 p.u., and the 60 Hz oscillation is still evident. These results are plotted in Figure 6 from which it is apparent that, with respect to surge current suppression, the return in improved performance from larger reactor size above approximately 12 mH diminished rapidly. Surge suppression would therefore not justify increasing the reactor above the 12 mH level.

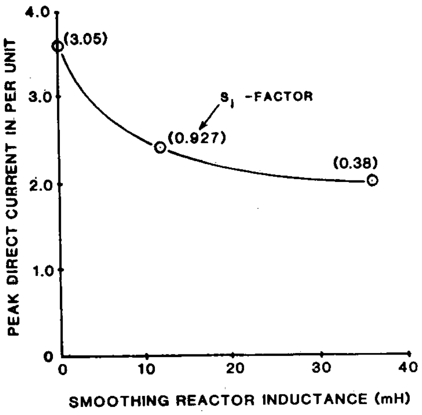

FIG. 6. Peak dc surge current as a function of size of dc smoothing reactor.

Earlier in this paper a factor S_i was introduced in Equation [1] which represented a per unit measure of the rate of rise of current. For the three values of smoothing reactor above, the S_i figures are 0.927, 3.05, and 0.38 ms^{-1}, respectively, and as shown in Figure 6 also. A higher value of S_i implies that the valve thyristors will need to be capable of handling higher currents during inverter bypass operation and commutation failures. Should the particular thyristors supplied have sufficient surge current capability, the absence of a small reactor should not prove to be limiting for this specific requirement.

DC and AC Side Harmonics

The smoothing reactor size affects harmonics on both the dc and the ac side, but these effects may be of minor consequence. Consideration of this factor alone would permit the use of a relatively small smoothing reactor. Table II presents information on direct current harmonic content for operation at 100 MW with smoothing reactor sizes of 12 mH and 0 mH. These field data were obtained during commissioning of a 200 MW (3600A DC) back-to-back converter.

Calculation of I_{rms} for the harmonics indicates a reduction from 88.7 to 54.3 A or approximately a 39% reduction with the introduction of a 12mH reactor.

There is inherent in the overall system design a tradeoff between the reduction in ripple on the dc system and control response/resonance frequency reduction. This is an area that needs to be examined carefully when designing a back-to-back system especially when being connected into weak ac systems.[6] While the current waveshape, and thus the dc harmonic content, improves with increasing inductance, the control responses slow down and the resonance frequency reduces making the stabilization for current control more difficult.

TABLE II
DC Current Frequency Spectra
$P_{dc} = 100$ MW, $I_d = 1800$ A

Frequency Hz	Current, A (L_d=12 mH)	Current, A (L_d=0 mH)
60	-	1.2
120	47.3	76.8
240	1.5	8.1
360	2.8	14.6
720	26.3	40.8
1440	2.0	2.3
2160	2.3	3.5
2880	1.8	3.5
3600	0.8	-

Figures 7(a) and 7(b) are frequency scan spectral analyses of the direct currents as reported in Table II taken over 2 scan ranges -- 0 Hz to 1 kHz and 10 kHz -- for a 12 mH smoothing reactor and no smoothing reactor, respectively.

Analyses were also conducted of the ac voltage waveforms at different converter loading with and without the smoothing reactor in the circuit. Field test data in Table III, Columns (A) and (B), are ac voltage without the smoothing reactor for 0 MW and 100 MW, respectively, while Column (C) is for the system at 100 MW with a 12 mH smoothing reactor.

A criteria normally applied for interference performance of ac filters is in terms of harmonic distortion, D_n, and total effective harmonic distortion, D_{eff}, defined as

$$D_n = \frac{V_n \times 100\%}{V_1}$$

and

$$D_{eff} = \sqrt{\sum_{n=2}^{50}\left(\frac{V_n \times 100}{V_1}\right)^2} \quad \text{in percent.}$$

Typical maximum levels for these factors are 1% for D_n for any harmonic and 2-5% for D_{eff}. Reviewing Table III, it is apparent that, with the exception of the 5th harmonic (300 Hz) with the dc system not operating (P_{dc} = 0 MW), the D_n criteria of 1% maximum for all harmonics is met. More significant is that the reduction in D_{eff} (from approximately 1% to <0.9%) appears to indicate that mere operation of the dc system even without a smoothing reactor reduces the total harmonic voltage distortion on the adjacent ac system. But, with addition of only a 12 mH reactor, D_{eff} was reduced to 55% of the value with no smoothing reactor (0.5%).

Consequently, this data appears to indicate that even though the smoothing reactor does reduce the voltage distortion on the ac system, that in fact, operation of the dc system itself with no reactor even contributes some degree of improvement, simply because of the presence of the normal complement of ac filters. The additional benefit to be derived from the reactor appears then to be marginal.

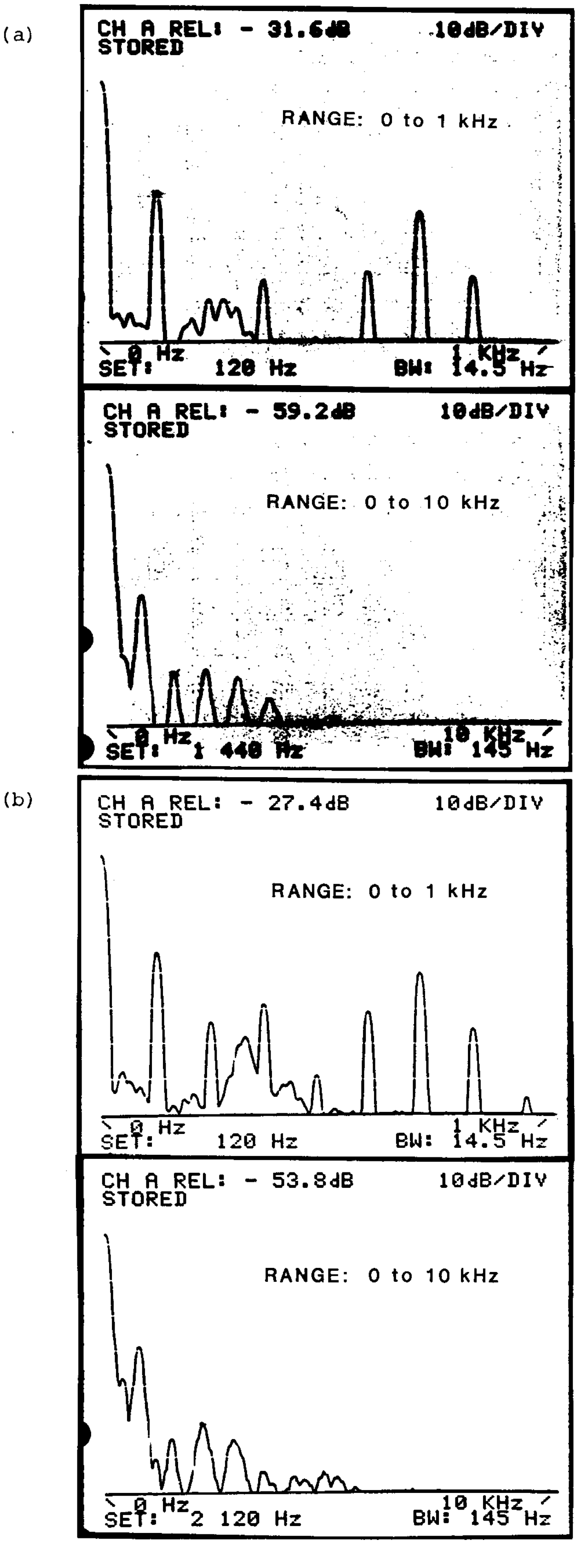

FIG. 7. Frequency scan, direct current,
(a) 12 mH smoothing reactor (L_d = 12 mH).
(b) no smoothing reactor (L_d = 0 mH).

TABLE III
AC Voltage Frequency Spectra

Frequency (Hz)	(A) AC Voltage (P_{dc} = 0 MW) (L_d = 0 mH) (p.u.)	(B) AC Voltage (P_{dc} = 100 MW) (L_d = 0 mH) (p.u.)	(C) AC Voltage (P_{dc} = 100 MW) (L_d = 12 mH) (p.u.)
60	1.0	1.0	1.0
180	1.1×10^{-3}	6.03×10^{-3}	2.4×10^{-3}
300	10.6×10^{-3}	6.1×10^{-3}	4.42×10^{-3}
420	0.95×10^{-3}	1.33×10^{-3}	--
540	0.57×10^{-3}	2.11×10^{-3}	1.27×10^{-3}
660	0.57×10^{-3}	0.64×10^{-3}	0.63×10^{-3}
780	0.27×10^{-3}	--	--
900	--	1.15×10^{-3}	1.01×10^{-3}

Figures 8, 9(a), and 9(b) are frequency scan spectral analyses of the ac voltages as reported in Table III.

It is concluded from the frequency scan information in Tables II and III that operation without the smoothing reactor is acceptable in this case with regards to harmonics, and that a 12 mH smoothing reactor without a spare is appropriate for this installation.

CONCLUSIONS

The paper highlights the functions that the dc smoothing reactor performs in the conversion process of a back-to-back dc system. Through the use of an example, the influence that the size of the dc smoothing reactor has on several performance indices was illustrated. Case studies demonstrated how varying the size of the reactor will affect the dc system performance with regards to inverter valve recovery volt- age distortion, bypass pair formation, commutation failures, and dc and ac harmonics.

Specific numerical results are of course limited to the particular example illustrated, but the tendencies perceived can be expanded with care into general conclusions. Among these would be

(1) for inverter valve recovery voltage distortion, only a relatively small reactor appears needed to derive adequate results,

(2) for bypass pair formation and commutation failure, beyond a very low value of reactor size, the return in terms of surge current reduction following formation of bypass pair diminishes rapidly, and

(3) a reduction in dc harmonics with the introduction of the dc reactor but the improvement in ac side voltage distortion was observed to be of only marginal value.

The significance of these general conclusions will vary between dc systems.

The results of this effort will help to build a more concrete basis for sizing the reactor in a particular dc system than can be exacted using material currently available to the general industry. It will help to build a better understanding of the factors influencing the size and their relative impact on performance of the dc system.

Operation of back-to-back systems with very low values of smoothing reactor inductance, and in fact with no reactor, is possible with very careful investigation of performance and scrutiny of outputs which can best be demonstrated at present on dc simulators.

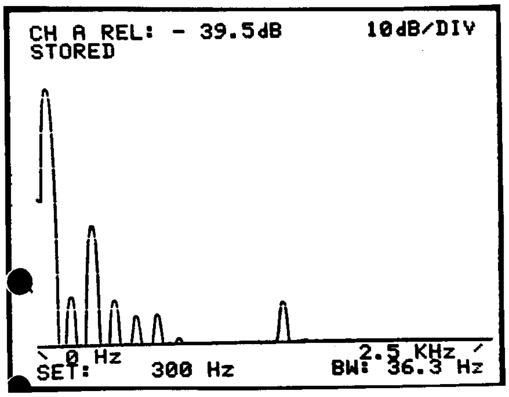

FIG. 8. Frequency scan, ac voltage, no smoothing reactor (L_d = 0 mH) and no dc power transmission.

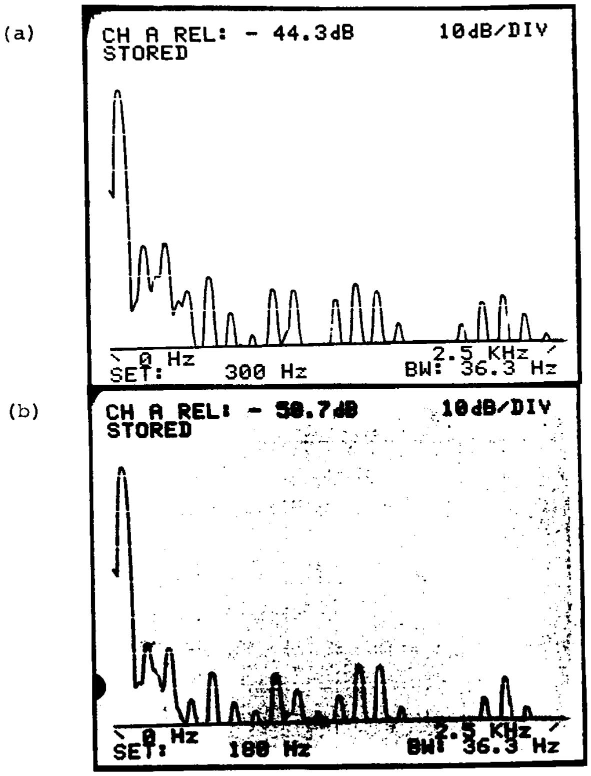

FIG. 9. Frequency scan, ac voltage, 100 MW dc power transmission:

(a) no smoothing reactor, L_d = 100 MW).

(b) 12 mH smoothing reactor, L_d = 12 mH.

Another application of the results of this type of investigation, could be the elimination of the need for spare or redundant reactors. For many systems, redundant and/or spare reactors may be unnecessary as the system may operate satisfactorily with only minor degradation in the various performance indices.

Current practice is to supply reactors in the 12 to 200 mH range which correlates to S_i-factors of 0.23 to 0.95 ms^{-1}. Conservatism has prevented the venturing into operation to date without reactors on a normal basis. With the further development of thyristors with greater surge current capability, the incentive exists to move towards eventual elimination of the discrete dc smoothing reactor for at least emergency operation if not normal operation for back-to-back dc systems. Studies which develop information on the performance of the dc system as impacted by the reactor will accelerate this desired eventuality.

Along this line, it is recommended that further work be done to determine mathematically the total harmonic current at the converter bus for a back-to-back system with the contribution of both converters superimposed, i.e., an extension of the conventional formulae currently available in textbooks which were derived for an ideal dc transmission system. Mathematical development of the equations would permit extension of these types of investigations to be performed on digital computers which are more readily available.

ACKNOWLEDGEMENT

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TABLE IV

DC Project	Rated System DC Voltage (kV)	BIL/BSL of Smoothing Reactor (kV)		BIL/BSL of DC System (kV)
		Terminal-Ground	Terminal-Terminal	
Eddy County	82	250	250	250/
Chateauguay	140.6	150	-	550/450
Acaray	25.6	125/100	125/100	125/100
Duernrohr	145	/380	/525	/380
Highgate	56	350	350	
Blackwater	57	200/120	200/170	
Eel River	80	350	350	350/
Tri-state	50	200	200	200/
Oklaunion	82	250	250	250/
Madawaska	130.5	470	550	470/390
Miles City	82	250	250	250/
Shin Shinanao	125	550	650	
Uruguaina Tie	17.9	95	95	95/
Sydney	50	110		250/210

Discussion

S. C. Kapoor (General Electric Co., Malvern, PA): The authors are to be congratulated for focusing on a subject that has not received much attention despite different practices. The selection of reactor size for a back-to-back scheme has been dictated by a number of factors as outlined by the authors. Generally speaking, a small size has been favored that would avoid discontinuities in the current and satisfy other performance criteria. Even where the studies have shown the possibility of operating a system without the reactor, the overall considerations including the risk factor have favored a finite reactor. This is particularly attractive where a relatively inexpensive dry-type reactor can be used. If a saving is to be made by excluding the reactor, then it must not be offset by increase in transformer inductance or other components.

Although the impact of the reactor on the ac-side harmonic distortion appears small as concluded by the authors, its role on the second harmonic on the dc side and the resulting third harmonic on the ac side may not be insignificant. A small size of the reactor may help reduce this interaction, especially in weak systems.

So far the back-to-back systems have been rated at relatively low dc voltage and high dc current, and the effects of stray capacitance on generation of noncharacteristic harmonics have not been experienced; however, if the voltage rating increases the role of the reactor may be important.

The authors have made an interesting comment in regards to (2), particularly in the case of asynchronous ac systems. For this equation, Kimbark [3] assumes six ideal conditions, including a perfectly constant dc voltage on the line side of the reactor. Thus the contribution of two terminals must be considered separately and superimposed. For the in-phase condition it would indeed be twice (arithmetic summation). However, for the synchronous systems a root-sum-square (RSS) may be used. A recent field measurement with Hydro-Quebec New England asynchronous link has indicated that harmonics indeed vary between 1.0 and 2.0 pu with time as the systems slip.

In regards to Table 1 and (1), would the authors comment on those schemes which have used a very low smoothing inductance or none at all, whether the transformer inductance (L) was made larger to compensate for the low smoothing inductance.

In Fig. 2, would the authors know of any specific advantage for the ungrounded method of connection (Method A). One might imagine that it might be because of the short-circuit current, but usually this has not been a problem unless the transformer inductance was considerably lower than typically used (14–18 percent). Disadvantages of such a system would be interference in voltage measuring circuits such as DCPT and high commutation transients. It is supposed that Method C includes those schemes which do not have direct grounding but use an RC network.

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CLOSURE

W. F. Long and D. J. Melvold: The authors would like to thank Dr. Kapoor for his insightful comments. We especially welcome his report on harmonic field current measurements in asynchronous systems, verifying that amplitude variations occur as the systems slip. We might add that this effect is also evident at power-line carrier frequencies. Cost savings in eliminating the smoothing reactor are thus partially counterbalanced by the need to increase PLC filtering.

The subject of stray capacitance and the generation of non-characteristic harmonic currents was first presented at the 1988 PES Winter Meeting [1] and was not inluded in our paper. We do not anticipate an increase in voltage ratings for back-to-back systems because of the economics of high-current thyristors. Table IV of the paper presents information on BIL levels that supports this point.

We are aware of only one system with no smoothing reactor. This is the McNeill Converter Station in Alberta, Canada, which will provide a 150 MW tie to the Saskatchewan grid. This converter station is now under construction. No special consideration has been given to the transformer design for this system. What is different is that the filters are connected to the transformer tertiary windings. This provides impedance between the filters and the system and minimizes effects of non-characteristic harmonics. The Alberta side will include a double-tuned third and fifth harmonic filter, as there are pre-existing low-order harmonic harmonic voltages on that bus.

Regarding the ungrounded connection in Figure 2 of our paper, our initial information on the Highgate system (Table I) was incorrect. Also, for Broken Hill, the minimum operating current level is "> 0" and to complete the table for the Vindhyachal project, values of 10mH and 1.94 for the reactor size and Si, respectively, could be inserted.

[1] E. V. Larsen, M. Sublich, and S. C. Kapoor, "Impact of Stray Capacitance on HVDC Harmonics", Paper No. 88 WM 082-0, IEEE PES Winter Meeting, New York, Feb., 1988.

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