Incorporation of Self-Commutating CSC Transmission in Power System Load-Flow

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Abstract*— This paper presents a method which incorporates self-commutated CSC transmission directly in a fast decoupled Newton-Raphson a.c. load flow. The d.c. equations are presented in a per unit form that is compatible with the per unit a.c. equations. A sequential method of solution is adopted in solving the load flow equations. The a.c. system equations are solved with the d.c. system modelled simply as a real and reactive power injection at the terminal busbar and for a d.c. solution, the a.c. system is modelled simply as a constant voltage at the converter a.c. terminal busbar. Further the new load flow program is tested for its effectiveness by carrying out several test cases.*This paper presents a method which incorporates self-commutated CSC transmission directly in a fast decoupled Newton-Raphson a.c. load flow. The d.c. equations are presented in a per unit form that is compatible with the per unit a.c. equations. A sequential method of solution is adopted in solving the load flow equations. The a.c. system equations are solved with the d.c. system modelled simply as a real and reactive power injection at the terminal busbar and for a d.c. solution, the a.c. system is modelled simply as a constant voltage at the converter a.c. terminal busbar. Further the new load flow program is tested for its effectiveness by carrying out several test cases.**

1. Introduction

The incorporation of conventional HVdc transmission in power flow analysis is now well established [1], the subject being sporadically revisited to reflect improvements in the control of the link, the use of more efficient numerical techniques or the type of algorithm more suited to a particular application.

Following the availability of more advanced switching devices with turn-off capability, and particularly the success of transistor type (IGBT) switching and PWM (Pulse Width Modulation) in the motor drive industry, a VSC HVdc transmission technology has recently been developed using these concepts. There are already six VSC-PWM transmission links in operation, the largest rating being 330MW, and a variety of multi-level VSC alternatives are also under consideration.

There are, however, limitations to the use of VSC technology, which make it uncompetitive with conventional CSC transmission for large powers and transmission distances.

With the addition of thyristor type self-commutating switches (GTO and IGCT) and multi-level topologies [2], the robust thyristor based CSC technology provides a very efficient solution, for large power and voltage ratings.

In multi-level CSC conversion the provision of independent control of the fundamental and harmonic frequency components would require varying the dc current level; however, CSC transmission, requires maintaining a constant dc current (or power) flow through the link; this relies on maintaining a constant voltage differential between the link terminals. As the ac terminal voltages will vary with respect to each other, the firing angles need to be altered to maintain the dc voltage differential, and this action affects the reactive powers. So for full steady state flexibility CSC transmission requires assistance of transformer OLTC.

This paper describes the incorporation of self-commutating CSC transmission in ac/dc power flow analysis, the basic tool for the assessment of the steady state operating conditions.

2. Steady State modelling of Self-Commutating Current Source Converters

The following simplifying assumptions are made in the selection of variables and the formulation of the converter equations.

1) The three ac voltages at the terminal busbar are balanced and sinusoidal.
2) Both the current and voltage on the converter side are perfect dc.
3) The converter transformer is lossless and its magnetizing admittance is ignored.
4) The two bridges attached to the same ac terminal busbar, are represented by an equivalent single bridge.

The two main factors affecting the different power flow behavior of self-commutated and conventional CSC conversion are:

Absence of commutation overlap: This results in considerable simplification of the equations controlling the transfer of current and voltage through the converter.

Unrestricted placement of the current waveform: The phase current can be leading or lagging, with respect to the corresponding phase voltage. this makes the converter a source or sink of reactive power, which eliminates the need for compensating equipment and provides greater flexibility for the control of the converter terminal voltage.

A. DC System Variables and Equations

Two independent variables are sufficient to model a dc converter in balanced power flow studies. However, the control

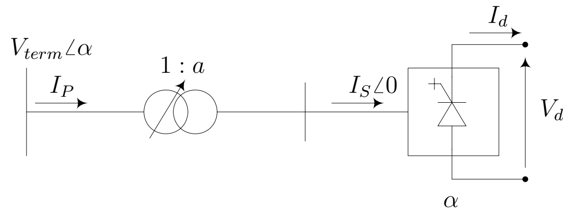

Fig. 1. Single phase equivalent circuit for basic converter

requirements of HVdc converters are such that a range of variables, or functions of them (e.g. constant power), are the specified conditions. If the minimum number of variables (two) are used, then the control specifications must be translated into equations of these two variables. These equations will often contain complex non-linearities, and present difficulties in their derivation and program implementation.

Figure 1 shows the converter equivalent circuit. In the absence of commutation overlap, the phase angle difference between the terminal voltage and the converter ac current is equal to the firing angle α; so using the converter current as a reference, the following variables are involved in the conversion process.

$V_{term}\angle\alpha$	converter terminal busbar nodal voltage
α	the firing angle
I_P, I_S	fundamental frequency components of the primary and secondary currents of the converter transformer
a	transformer off-nominal tap ratio
V_d	average dc voltage
I_d	converter direct current

However, the variables I_P and I_S can be eliminated, as they are not directly controlled by the converter or explicitly involved in the derivation of the converter terminal conditions.

The use of variable 'a' needs some justification. In multilevel CSC, independent control of the fundamental and harmonic frequency components can only be achieved by varying the dc current level. This action, however, is not possible in CSC transmission, which requires maintaining a constant dc current (or power) flow through the link; this relies on maintaining a constant voltage differential between the link terminals. As the ac terminal voltages will vary with respect to each other, the firing angles need to be altered to maintain the dc voltage differential, and this action affects the reactive powers. So for full state flexibility (similar to that of the VSC-PWM) CSC transmission requires the assistance of transformer OLTC. A possible alternative is to sacrifice some of the harmonic reduction by introducing an element of current pulse width modulation to control the converter ac current fundamental component, without altering the dc current level.

The following relationships (in p.u.) are derived in terms of the selected four variables (V_d, I_d, a, α).

The dc voltage may be expressed in terms of the ac system voltage referred to the transformer secondary, i.e.

$$V_d = k \cdot a \cdot V_{term} \cos\alpha \qquad (1)$$

where

$$k = \frac{3\sqrt{2}}{\pi}$$

The dc current and voltage are related by the dc system configuration.

$$f(V_d, I_d) = 0 \qquad (2)$$

Two more equations are required to match the four variable system at each end of the link. These are derived from the specified control mode. Typical control specifications are: dc voltage

$$V_d - V_d^{sp} = 0$$

dc current

$$I_d - I_d^{sp} = 0$$

dc power

$$V_d \cdot I_d - P_{dc}^{sp} = 0$$

converter firing angle

$$\alpha^{sp} - \alpha = 0$$

During the iterative solution procedure, an uncontrolled converter variable may go outside pre-specified limits. When this occurs, the offending variable is held to its limit value and replaced by an appropriate control specification. For instance if 'a' exceeds the maximum value, the α is freed and last specification is replaced by

$$a^{sp} - a = 0$$

3. Structure of the ac-dc Load Flow

The operating state of a combined ac-HVdc power system is defined by the vector $[\overline{V}, \overline{\theta}, \overline{x}]^T$ where

$\overline{V}$	is a vector of the voltage magnitude at all ac system busbars
$\overline{\theta}$	is a vector of the angles at all ac system busbars (except the reference bus which is assigned θ=0)
$\overline{x}$	is the vector of dc variables described in Section 2-1, i.e. $[V_d, I_d, a, \alpha]^T$

In the Newton-Raphson load flow solution the equations that relate to the ac system variables are derived from the specified ac system operating conditions. The only modification required to the usual real and reactive power mismatches are in the interface equations at the converter terminal busbars, i.e.

$$P_{term}^{sp} - P_{term}(ac) - P_{term}(dc) = 0 \qquad (3)$$

$$Q_{term}^{sp} - Q_{term}(ac) - Q_{term}(dc) = 0 \qquad (4)$$

where

$P_{term}(ac)$ and $Q_{term}(ac)$	the injected active and reactive power at the terminal busbar as a function of the ac system variables
P^{sp}_{term}	represents an ac system load at the converter busbar
$P_{term}(dc)$ and $Q_{term}(dc)$	are functions of the converter ac terminal busbar voltage and of the dc system variables, i.e.

$$\begin{aligned} P_{term}(dc) &= f(V_{term}, \overline{x}) \\ &= V_d \cdot I_d \end{aligned} \quad (5)$$

and

$$\begin{aligned} Q_{term}(dc) &= f(V_{term}, \overline{x}) \\ &= V_{term} \cdot I_p \cdot \sin\alpha \\ &= V_{term} \cdot k \cdot a \cdot I_d \cdot \sin\alpha \end{aligned} \quad (6)$$

This equations derived from the specified ac system conditions may, therefore, be summarized as:

$$\begin{bmatrix} \Delta\overline{P}(\overline{V}, \overline{\theta}) \\ \Delta\overline{P}_{term}(\overline{V}, \overline{\theta}, \overline{x}) \\ \Delta\overline{Q}(\overline{V}, \overline{\theta}) \\ \Delta\overline{Q}_{term}(\overline{V}, \overline{\theta}, \overline{x}) \end{bmatrix} = 0 \quad (7)$$

where the mismatches at the converter terminal busbars are indicated separately. A further set of independent equations are derived from the dc system conditions. These equations, designated,

$$\overline{R}(V_{term}, \overline{x})_k = 0 \quad (8)$$

are:

$$\begin{aligned} R(1) &= V_d - k \cdot a \cdot V_{term} \cos\alpha \\ R(2) &= f(V_d, I_d) \\ R(3) &= \text{control specification} \\ R(4) &= \text{control specification} \end{aligned}$$

As explained earlier, the dc system equations are made independent of the ac system angle $\overline{\theta}$ by selecting a separate angle reference for the dc system variables as shown in Figure 1. This improves the algorithmic performance by effectively decoupling the angle dependence of ac and dc systems.

The general ac-dc load flow problem may, therefore, be summarized as the solution of:

$$\begin{bmatrix} \Delta\overline{P}(\overline{V}, \overline{\theta}) \\ \Delta\overline{P}_{term}(\overline{V}, \overline{\theta}, \overline{x}) \\ \Delta\overline{Q}(\overline{V}, \overline{\theta}) \\ \Delta\overline{Q}_{term}(\overline{V}, \overline{\theta}, \overline{x}) \\ \overline{R}(V_{term}, \overline{x}) \end{bmatrix} = 0 \quad (9)$$

A. Sequential solution

In a sequential solution the following three equations are solved iteratively to convergence.

$$\begin{aligned} [\Delta\overline{P}/\overline{V}] &= [B'][\Delta\overline{\theta}] \quad (10) \\ [\Delta\overline{Q}/\overline{V}] &= [B''][\Delta\overline{\theta}] \quad (11) \\ [\overline{R}] &= [A][\Delta\overline{x}] \quad (12) \end{aligned}$$

(10) and (11) are those of the standard ac system Fast Decoupled algorithm with the dc modelled as real and reactive power injection at the appropriate terminal busbar. (12) is the dc solution, with the ac system modelled as a constant voltage at the converter terminals.

This iteration sequence, referred to as P, Q, DC is illustrated in the flow chart of Figure 2 and may be summarized as follows:

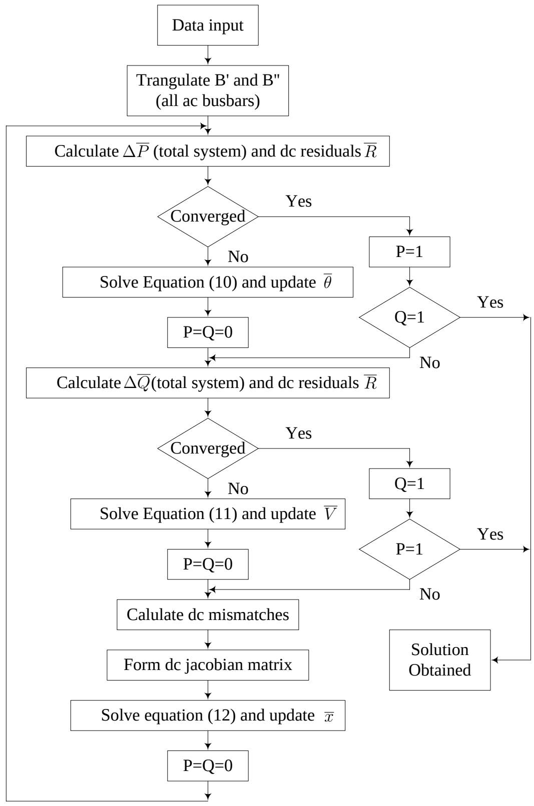

Fig. 2. Flow chart for sequential a.c./d.c. load flow

1) Calculate $\Delta\overline{P}/\overline{V}$, solve (10) and update $\overline{\theta}$
2) Calculate $\Delta\overline{Q}/\overline{V}$, solve (11) and update $\overline{V}$
3) Calculate dc residuals, $\overline{R}$, solve (12) and update $\overline{x}$
4) Return to 1

Alternatively, the dc equations can be solved after each real power as well as after each reactive power iteration and the resulting sequence is referred to P, DC, Q, DC.

With the sequential method, the dc equations need not be solved for the entire iterative process. Once the dc residuals have converged, the dc system may be modelled as fixed real and reactive power injections at the converter terminal busbars. The residuals must still be checked after each iteration to ensure that the dc system remains converged.

4. Test System and Results

A simple interconnection, shown in Figure 3 is used to verify the effectiveness of the selected control specifications under different a.c. system strengths. The system impedance on the receiving end (converter 2) is varied to obtain different SCR (Short Circuit Ratio) values while the system impedance on the sending end is kept constant at 0.1pu, thus resulting in a constant SCR of 10.

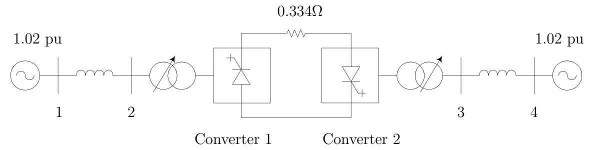

Fig. 3. Test system for the load flow study

The dc link data and specified controls for the test cases are respectively given in Tables I and II. The results from the load flow program is given in Table III. In Table III, from cases 1 to 4, the receiving end voltage shows a reducing pattern. This is due to the ac system strength at the receiving end getting weaker. However the converter operating point is unaltered in all four cases due to the transformer tap changer action. In case 5, the receiving end voltage is restored again to a considerable level by supplying more reactive power from the converter.

TABLE I
CHARACTERISTICS OF THE DC LINK

	Converter 1	Converter 2
a.c. busbar	2	3
d.c. voltage base	100kV	100kV
Transformer reactance	0.1pu	0.1pu
d.c. line resistance	0.334Ω	

Therefore from these results it can be concluded that the self-commutating CSC, with the assistance of OLTC (off load tap changer) can achieve flexibility levels of existing PWM-VSC HVdc links.

5. CONCLUSIONS

The conventional CSC HVdc load flow algorithm has been modified to represent the more flexible characteristics of self-commutating conversion. The absence of commutation overlap has been shown to simplify the converter model considerably. Aided by converter transformer off load tap changer, OLTC (which is also part of the conventional line commutated HVdc solution) the self commutating version provides full flexibility in the transfer of active and reactive power, thus giving a level of controllability similar to that of the recently implemented PWM-VSC HVdc schemes.

The modified algorithm has shown to provide good convergence even with a sequential solution.

Considering its greater efficiency over the PWM-VSC version, self-commutating thyristor based HVdc is likely to continue being a competitive option for high voltage and large power applications.

REFERENCES

[1] J. Arrillaga and N. R. Watson, *Computer modelling of Electrical power systems*, 2nd ed. John Wiley ans Sons, London, 2001.
[2] Y. H. Liu, "Multi-level voltage and current reinjection AC-DC conversion," Ph.D. dissertation, University of Canterbury, November 2003.

TABLE II
SPECIFIED CONTROLS FOR THE TEST CASES

Case	Receiving end SCR	Converter	dc voltage, V_{dc} (kV)	Control angle, α (degrees)	Transformer tap, a (percentage)	Terminal active power, P_{dc} (MW)	Terminal reactive power, Q_{dc} (MVAr)
1	10	1				58.6	-5
		2	-130				-5
2	5	1				58.6	-5
		2	-130				-5
3	2.5	1				58.6	-5
		2	-130				-5
4	1.25	1				58.6	-5
		2	-130				-5
5	1.25	1				58.6	-5
		2	-130				-15

APPENDIX - PER UNIT SYSTEM

Computational simplicity is achieved by using common power and voltage base parameters on both sides of the converter, i.e. the a.c. and d.c. sides. Consequently, in order to preserve consistency of power in per unit, the direct current base, obtained from $\frac{MVA_B}{V_B}$, has to be $\sqrt{3}$ times larger than the a.c. current base.

This has the effect of changing the coefficients involved in the a.c./d.c. current relationships. For instance, for the perfectly smooth direct current, the r.m.s. fundamental components of the phase current is related to I_d by the expression,

$$I_S = \frac{\sqrt{6}}{\pi} \cdot I_d$$

and translating the above equation into per unit yield,

$$I_S(p.u.) = \frac{\sqrt{6}}{\pi} \cdot \sqrt{3} I_d(p.u.)$$

TABLE III
RESULTS FROM THE LOAD-FLOW STUDIES

Case	Converter	Converter terminal voltage (pu)	Transformer tap, a (percentage)	Control angle, α (degrees)	dc current, I_{dc} (A)	dc voltage, V_{dc} (kV)	Terminal active power, P_{dc} (MW)	Terminal reactive power, Q_{dc} (MVAr)
1	1	1.0233	5.7936	-4.8769	450.2	130.1504	58.6000	-5
	2	1.0233	5.9154	-175.1175	450.2	-130.0000	-58.5323	-5
2	1	1.0233	5.7935	-4.8769	450.2	130.1504	58.6000	-5
	2	1.0132	4.8742	-175.1175	450.2	-130.0000	-58.5322	-5
3	1	1.0233	5.7935	-4.8769	450.2	130.1504	58.6000	-5
	2	1.0022	3.7586	-175.1175	450.2	-130.0000	-58.5322	-5
4	1	1.0233	5.7935	-4.8769	450.2	130.1504	58.6000	-5
	2	0.9299	-3.7490	-175.1175	450.2	-130.0000	-58.5322	-5
5	1	1.0233	5.7935	-4.8769	450.2	130.1504	58.6000	-5
	2	1.0295	3.5958	-175.1175	450.2	-130.0000	-58.5322	-15