Reactive Power Control in Multi-group IGBT Based Current-Sourced HVDC Interconnections

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Abstract: Self-commutating multilevel current reinjection is a potential alternative to conventional HVDC thyristor technology. An important drawback of the multilevel configurations is the interdependence of the reactive power injections at both ends of the link. This paper describes a new concept applicable to large power converters consisting of two series-connected twelve-pulse groups. It is based on the use of a controllable shift between the firings of the two twelve-pulse groups in opposite directions, a new concept that provides independent reactive power control at the sending and receiving ends. The theory is verified by EMTDC simulation.

Keywords: Pulse Width Modulation (PWM), High Voltage Direct Current (HVDC), Multi Level Current Reinjection (MLCR).

I. INTRODUCTION

Owing to their structural simplicity and four quadrant power controllability, pulse width modulation (PWM) conversion has so far been the preferred option for self-commutating medium power HVDC transmission. However, this technology is less suited to large power ratings and long distances, due to higher switching losses and to the rating limitations of its main components (namely the power transistor switch and underground cable). Thus the interchange of large quantities of power between separate power systems and the transmission of power from remote generating stations are still based on the principle of line-commutated current source conversion. Multilevel VSC configurations have been presented as possible alternatives to PWM-VSC Transmission, but their structural complexity has been the main obstacle to their commercial implementation. A recent proposal, the multilevel current reinjection (MLCR) concept, simplifies the converter structure and permits the continued use of conventional IGBTs for the main converter bridges.

The main advantage of self over natural-commutation in HVDC transmission is the ability to control independently the reactive power at each end of the link, a property that cannot be achieved by MLCR-based (or any other multilevel) configuration when using only one double-bridge converter group. However, interconnections of large power ratings will normally use two or more 12-pulse converter groups and these can be controlled independently from each other without affecting the output voltage waveform. This fact constitutes the basis of the new control scheme proposed here. When the operating condition at one end of the link alters the reactive power balance at this end, the firings of the two groups at the other end are shifted with respect to each other in opposite directions to keep the power factor constant.

II. HIGH VOLTAGE DIRECT CURRENT

Over long distances bulk power transfer can be carried out by a high voltage direct current (HVDC) connection cheaper than by a long distance AC transmission line. HVDC transmission can also be used where an AC transmission scheme could not (e.g. through very long cables or across borders where the two AC systems are not synchronized or operating at the same frequency). However, in order to achieve these long distance transmission links, power convertor equipment is required, which is a possible point of failure and any interruption in delivered power can be costly. It is therefore of critical importance to design a HVDC scheme for a given availability. The HVDC technology is a high power electronics technology used in electric power systems. It is an efficient and flexible method to transmit large amounts of electric power over long distances by overhead transmission lines or underground/submarine cables. It can also be used to interconnect asynchronous power systems. The fundamental process that occurs in an HVDC system is the conversion of electrical current from AC to DC (rectifier) at the transmitting end and from DC to AC (inverter) at the receiving end. There are three ways of achieving conversion:

- Natural commutated converters
- Capacitor Commutated Converters
- Forced Commutated Converters

A. Natural Commutated Converters (NCC)

NCC are most used in the HVDC systems as of today. The component that Enables this conversion process is the IGBT, which is a controllable semiconductor that can carry very high currents (4000 A) and is able to block very high voltages (up to 10 kV). By means of connecting the IGBTs in series it is...

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possible to build up a IGBT valve, which is able to operate at very high voltages (several hundred of kV). The IGBT valve is operated at net frequency (50 Hz or 60 Hz) and by means of a control angle it is possible to change the DC voltage level of the bridge.

B. Capacitor Commutated Converters (CCC)
An improvement in the IGBT-based Commutation, the CCC concept is characterized by the use of commutation capacitors inserted in series between the converter transformers and the IGBT valves. The commutation capacitors improve the commutation failure performance of the converters when connected to weak networks.

C. Forced Commutated Converters (FCC)
This type of converters introduces a spectrum of advantages, e.g. feed of passive networks (without generation), independent control of active and reactive power, power quality. The valves of these converters are built up with semiconductors with the ability not only to turn-on but also to turn-off. They are known as VSC (Voltage Source Converters). A new type of HVDC has become available. It makes use of the more advanced semiconductor technology instead of IGBTs for power conversion between AC and DC. The semiconductors used are insulated gate bipolar transistors (IGBTs), and the converters are voltage source converters (VSCs) which operate with high switching frequencies (1-2 kHz) utilizing pulse width modulation (PWM).

D. Configurations of HVDC
There are different types of HVDC systems which are

Mono-polar HVDC System: In the mono-polar configuration, two converters are connected by a single pole line and a positive or a negative DC voltage is used. In Fig.1 there is only one Insulated transmission conductor installed and the ground or sea provides the path for the return current.

Fig.1. mono polar hvdc system.

Bipolar HVDC System: This is the most commonly used configuration of HVDC transmission systems. The bipolar configuration, shown in Fig.2. Uses two insulated conductors as Positive and negative poles. The two poles can be operated independently if both Neutrals are grounded. The bipolar configuration increases the power transfer capacity. Under normal operation, the currents flowing in both poles are identical and there is no ground current. In case of failure of one pole power transmission can continue in the other pole which increases the reliability. Most overhead line HVDC transmission systems use the bipolar configuration.

E. Voltage Source Converter based on IGBT Technology
The modular low voltage power electronic platform is called Power Pak. It is a power electronics building block (PEBB) with three integrated Insulated Gate Bipolar Transistor (IGBT) modules. Each IGBT module consists of six switches forming three phase legs. Various configurations are possible. For example three individual three-phase bridges on one PEBB, one three phase bridge plus chopper(s) etc. The Power Pak is easily adaptable for different applications. The IGBT modules used are one Power Pak as it is used for the SVR. It consists of one three-phase bridge (the three terminals at the right hand side), which provides the input to the DC link (one IGBT module is used for it) and one output in form of one single phase H-bridge (the two terminals to the left) acting as the booster converter. For the latter two IGBT modules are used with three paralleled phase legs per output terminal. By parallelising such PEBBs adaptation to various ratings is possible.

F. GTO/IGBT (IGBT based HVDC)
Normal IGBTs (silicon controlled rectifiers) are not fully controllable switches (a "fully controllable switch" can be turned on and off at will.) IGBTs can only be turned ON and cannot be turned OFF. IGBTs are switched ON by a gate signal, but even after the gate signal is de-asserted (removed), the IGBT remains in the ON-state until any turn-off condition occurs (which can be the application of a reverse voltage to the terminals, or when the current flowing through (forward current) falls below a certain threshold value known as the holding current.) Thus, a IGBT behaves like a normal semiconductor diode after it is turned on or "fired". The GTO can be turned-on by a gate signal, and can also be turned-off by a gate signal of negative polarity. Turn on is accomplished by a positive current pulse between the gate and cathode terminals. As the gate-cathode behaves like PN junction, there will be some relatively small voltage between the terminals. The turn on phenomenon in GTO is however, not as relievable as an IGBT(IGBT) and small positive gate current must be maintained even after turn on to improve reliability. Turn off is accomplished by a negative voltage pulse between the gate and cathode terminals. Some of the forward current (about one third to one fifth) is "stolen" and used to induce a cathode-gate voltage which in turn induces the forward current to fall and the GTO will switch off (transitioning to the 'blocking' state.) GTO IGBTs suffer from long switch off times, whereby after the forward current falls, there is a long tail time where residual current continues to flow until all remaining charge from the device is taken away. This restricts the maximum switching frequency to approx 1kHz. It may however be noted that the turn off time of a comparable IGBT is ten times that of a GTO. Thus switching frequency of GTO is much better than IGBT.

III. CONTROL STRUCTURE
For complete flexibility the sending end needs to control real and reactive power and the receiving end keep the converter dc voltage constant (so as to minimize dc current for
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With reactive power control at both ends, the controllers can easily be configured for optimum power transfer at the system level depending on operating objectives, which usually involves providing constant power factor at the sending end and constant ac terminal voltage at the receiving end. In order to control the real and reactive power over the complete operating range the converter response needs to be linear. Standard PID controllers are unsuitable for this application as their gain is static, and although they may give suitable performance over a narrow band, the latter is not acceptable over the complete range. This is explained in more detail later. Fig.3. illustrates the control ranges of the real and reactive power responses for a values of $\pm 90^\circ$. It is clear that these controller surfaces are very nonlinear, and it is not hard to understand why a linear PID controller would be unsuitable.

Given the aforementioned controller surfaces, it is difficult to visualize how the controller must perform, especially since the controller firing angles are expected to operate equally well in the positive and negative regions. What is needed is a controller that operates for all combinations of $P$ and $Q$ without the need to manually switch controller gains and control actions. An example of four controller operating conditions is shown in Fig.4. These diagrams show that the controller is expected to operate over a wide range of conditions and that the change in firing angle has the greatest influence on the real power near the X axis and on the reactive power near the Y axis. This is better explained by examining the real and reactive power contribution of one converter in isolation. The real power transferred by the converter depends on the cosine of the firing angle $\alpha_1$ while the reactive power depends on the sine of $\alpha_1$. What is of interest to control system designers is the rate of change of the controlled outputs $P$ and $Q$, as this determines the level of gain (or sensitivity) in system response. Basic differentiation reveals that the rate of change is proportional to $-\sin(\alpha_1)$ for real power and to $\cos(\alpha_1)$ for reactive power, which makes this system very nonlinear.

As mentioned earlier, conventional controller operation is confined to a relatively small range and functions with a fixed gain, thereby assuming that the system is linear over the small range. This control philosophy becomes even less suitable when we consider that an ideal independent and fully flexible controller should be able to provide a combination of $\alpha_1$ and $\alpha_2$ that satisfies the requirements of both $P$ and $Q$ simultaneously. Fig.5 illustrates a simplified block diagram of what the controller must achieve, the goal being a mapping function that translates $P$ and $Q$ into $\alpha_1$ and $\alpha_2$, to make the nonlinear converter appear linear. In doing this, then linear control theory may be used successfully.

The only information representing the behavior of the converter system is given by the steady state (8) and (9), but this is sufficient initially, because they show the influence that $\Delta\alpha_1$ and $\Delta\alpha_2$ have on the output variables $P$ and $Q$. Using the partial differentials of the steady state equations to $P$ and $Q$ in Matrix A, it is possible to model the converter systems transient response (but not the system state). If the matrix is nonsingular, its inverse can be used to linearize the converter system behavior. The inverse of Matrix A, with the common gain component grouped on the left side, becomes

$$A^{-1} = \frac{1}{3V_I^2 \sin(\alpha_1 - \alpha_2)} \begin{bmatrix} -\cos(\alpha_2) & -\sin(\alpha_2) \\ \cos(\alpha_1) & \sin(\alpha_1) \end{bmatrix}$$

Fig.4. Firing shift control providing (a) large P and Q, (b) large Q and smaller P, (c) small P and Q, and (d) large P, no Q.

Fig.5. Block diagram of the nonlinear system control objective.

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This equation indicates that the overall system gain depends on the difference between the two firing angles \((\sin(\alpha_1 - \alpha_2))\) and the contribution of (for P) real power on the other groups firing angle, and (for Q) reactive power contribution on the other groups firing angle. While making sense in theory, this needs to be realized in practice. Examining the system on an incremental basis (i.e., from \(\alpha_2 \to \alpha_1 + \delta\alpha_1\)), as the difference is reduced, the accuracy is increased, becoming very close to the continuous integral equivalent. It could be argued that in each partial differential equation, the effect of \(\Delta\alpha_1\) on \(\Delta\alpha_2\) and vice versa is not fully captured, but in a practical system this effect can be minimized with suitable feedback.

A. Practical Implementation

Figs. 6 and 7 show how the implementation of the theory into a real system controller. In Fig. 6, the controller has two separate channels, one for each of the \(P\) and \(Q\) components. For each channel, the theory is the same; the error is calculated by subtracting the measured power from the power order, and this is fed into the PID controller. The increment of \(\Delta P\) and \(\Delta Q\) becomes the input into the nonlinear mapping function, which resolves the increment of \((\Delta\alpha_{1P}\text{and }\Delta\alpha_{2P})\) and \((\Delta\alpha_{1Q}\text{and }\Delta\alpha_{2Q})\) from the and channels, respectively. The nonlinear errors are combined and then \(\Delta\alpha_P\text{and }\Delta\alpha_Q\) are integrated to provide the required outputs \((\alpha_P)\) and \((\alpha_Q)\) as inputs into the converter firing logic.

(Fig. 6). Implementation of nonlinear control theory.

The nonlinear mapping function in Fig. 6 for \(P\) is represented by \(A_{1P}^1\cdot A_{2P}^1\), and for \(Q\) is \(A_{1Q}^1\cdot A_{2Q}^1\), in (17). Fig. 7 shows how the system is realized in a practical controller. The controller layout follows almost exactly the analytical development from (10) to (17), with only additional low pass filters added to prevent ringing when the error is almost zero. It is important to note that the common component of the converter control is calculated separately [Fig. 7], since this determines the overall gain of the system. Hard limits on the calculation are provided so as to prevent wind up and instability which can occur if \(\alpha_1 = \alpha_2\). Also to ensure that firing angle \(\alpha_1\) is always greater than \(\alpha_2\), limits are placed on the integrators. The receiving end controller topology is much the same as that of the sending end, but as it must control \(V_{dcR}\) and \(Q_{dc}\), the layout is different. Using steady state (5) and (9), the inverse transfer function becomes

\[
A^{-1} = \frac{1}{3V_T^2 \sin(\alpha_1 - \alpha_2)} \left[ \frac{-\sqrt{2} \cos(\alpha_1)}{4} \frac{-\sin(\alpha_2)}{I_1} \right]
\]

(Fig. 7). Sending end controller block diagram, with the main linearizing components in (a) and the common angle difference calculation in (b).

Given the steady-state equations and taking into consideration (6), it becomes apparent that although full control is justified by the theory, the range of \(Q\) control depends on the magnitude of \(I_{dc}\). Optimum dc power transmission occurs when the dc current is minimized, as this also minimizes the dc link power losses; however this affects the range of \(Q\) controllability at both the sending and receiving ends. As the reactive power circulation is confined to the ac system side, the magnitude of the ac current in each converter group determines the level of reactive power controllability in the ac system. The real power, which is also a function of the ac current magnitude, is determined by the combination of \(V_{dc}\) and \(I_{dc}\) on the dc link. To understand the reactive power controllability limits, it must be realized that the same amount of real power can be transferred with a combination high \(V_{dc}\)/low \(I_{dc}\), or low \(V_{dc}\)/high \(I_{dc}\).

An example of this in a multi group MLCR, in per unit terms is given

\[
\begin{align}
\text{High } V_{dc} : & \quad P_{dc} = 1pu = 5.5puV_{dc} \times 0.182puI_{dc} \\
\text{Low } V_{dc} : & \quad P_{dc} = 1pu = 2.25puV_{dc} \times 0.364puI_{dc}
\end{align}
\]
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And so with \( I_1 = \sqrt{3} m_i I_{dc} \) and \( V_{oc} \) being the same in both cases, (9) shows that (20) would yield twice the reactive power for a given firing angle as (19). So with conflicting objectives in real power efficiency and reactive power controllability, a compromise must be made between control range and overall efficiency during system design.

IV. DYNAMIC SIMULATION AND RESULTS

A. Test System

The test circuit is a simplified HVDC link configuration with the two interconnected systems represented as

![Fig.8. Simulation diagram of thyristor based HVDC Converter.](image)

Thevenin equivalents. As shown in Fig.8, each terminal consists of two five-level MLCR converter groups. Using 1000 MW and 220 kV as base values, the source voltages are set at 1.04 and 1.02 p.u. at the sending and receiving ends, respectively. The series impedances at the sending and receiving ends are set to 0.2 p.u. to represent systems with SCRs of approximately 3.1, and the transformer leakage reactance of all converter transformers is equal to 0.1 p.u. The dc line is represented by a resistance of 0.2 p.u. in series with a 2H smoothing inductor. The active power transfer and reactive power are the controlled variables at the sending end; at the receiving end the controlled variables are the dc voltage and the reactive power order.

B. Simulation Verification and Reactive Power Independence

The test system has been modelled using the MATLAB package and the response to a series of step changes over a 3-s period are presented in Fig.9. Changes in the active power order from 1000 to 1400 MW (at 0.4 s) and from 1400 to 800 MW (at 0.74 s) are shown in Fig.9(a); their effect on the reactive power at either end of the link is shown in graphs (b) and (f) to be negligible. Likewise, Fig.9(b) shows step changes in the reactive power order at the sending end, first from 0 to 100 MVA (at 1.4 s) and later from 100 to 200 MVA (at 1.7 s); the effect on the receiving end active and reactive power (shown in graphs (e) and (f), respectively) are also negligible and they only cause a slight disturbance to the active power at the sending end [as shown in graph (a)]. The effect of the above changes on the group firings at the sending end, illustrated in graph (c), show that a1B can operate with positive and negative values, thereby minimizing the reactive power circulation between the groups [clearly noticeable between 1.4 and 1.7 s in graph (d)]. Fig.9(f) shows a change in the reactive power order at the receiving end, from 0 to 100 MVA (at 2.24 s) and from 100 to 200 MVA (at 2.4 s). These produce a small change of active power, which requires a small correction in the firing angle, but no visible change is observed in the sending end reactive power [graph (b)]. As the secondary control objective is to maintain dc voltage constant, a maximum step of 100 MVA is possible at the receiving end. This is because the receiving end terminal voltage decreases as more reactive power is required by the converter, which further contributes to the decrease in dc voltage for a given firing angle.

C. IGBT based Simulation Verification and Reactive Power Independence

The dynamic simulation in MATLAB features the effect of four separate controllers, one for each of the reactive powers, and one for the sending end real power and receiving end dc voltage as shown in Fig.10. By adding an extra controller to each of the reactive power orders, it is possible to control the system to provide unity power factor and constant terminal voltage over the complete real power operating range. The sending end correction is made from the point of view of the ac system, so the converter controller is configured to maintain the power factor of the main supply transmission line as well. In practice it may not be possible to calculate the
impedance of the supply in all cases, and an approximation would have to be made about a “nominal” correction point. At the receiving end, the control of the terminal voltage should be easier to achieve, as the nominal supply voltage would be known, or could be calculated. This could also be adjusted manually by the system operator to provide additional voltage support as necessary. Fig.11(a)–(f) presents an example of the multigroup MLCR dc link providing power factor correction and terminal voltage control.

Fig.10. Simulation diagram of IGBT based HVDC Converter.

Fig.11. IGBT based Voltage, Real and reactive power order changes at the sending and receiving ends.

To highlight the dynamics of the control method, the real power order is modified in (a) in a series of steps, as listed. The reactive power responses are plotted in Fig.11(b) and (e) for the sending and receiving ends, respectively, and the sending end power factor in (c). In (f), the constant line represents the receiving end source, and the second line is the terminal voltage. It is important to note in (e) and (f), that under this control scheme (i.e., with optimized V_{dc}) for real power transfers of 240 and 400MW, the ac current at the receiving end is insufficient to provide stable terminal voltage control. This highlights one of the limitations of maximizing V_{dc}; although, however, this can be easily corrected by reducing V_{dc} during situations where low real power transfer is required.

V. CONCLUSION

A new type of IGBT/Diode converter control has been developed, applicable to multilevel HVDC schemes with two or more 12-pulse groups per terminal. By using IGBT/Diode converter to reduce the switching losses and improve the active power on ac side because of switching frequency higher than IGBT based converters. It has been shown theoretically, and verified by MATLAB simulation using an MLCR configuration, that the use of a controllable shift between the firings of the series connected converter groups permits independent reactive power control at the two dc link terminals. This provides four quadrant power controllability to multilevel current source HVDC transmission and, thus, makes this alternative equally flexible to PWM-controlled voltage source conversion, without the latter’s limitations in terms of power and voltage ratings. It can be expected that MLCR, combined with firing-shift control, should compete favorably with the conventional current source technology for very large power applications.

VI. REFERENCES

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