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(54) Title: A DIRECT CURRENT POWER TRANSMISSION SYSTEM AND ASSOCIATED CONTROL METHOD

(57) **Abstract:** A method of selecting the appropriate direct voltage and direct current in order to operate a direct current power transmission link such that approximately constant reactive power absorption is exhibited from zero power transfer to rated power transfer.

A direct current power transmission system and associated control method

The present invention relates to a direct current power transmission system which interconnects two alternating current electrical busbars, and to an associated control method.

In the transmission of electrical power, it is sometimes economical to convert alternating current electrical power to direct current for transmission and then convert back to alternating current. The justification for the conversion may be either economic or to provide an asynchronous connection.

The value of the power transmitted by the direct current circuit is the resultant of the multiplication of the scalar quantities of direct voltage and direct current.

In many known direct current power transmission systems, the direct voltage is maintained constant for power transmission in one direction whilst the power is varied by adjusting the direct current.

The direct current can, in some systems, be reduced to less than ten percent of the rated current. In such circumstances, it may be necessary to impose a minimum direct current limit in order to avoid the direct current becoming discontinuous. This minimum direct current will, in such circumstances, lead to a minimum direct power limit.

In some direct current transmission systems, this basic concept has been modified such that, particularly when starting from a high power transmission level, an initial reduction in the power transmission demand is accounted for by a step reduction in direct voltage (in order to reduce the thermal and electrical stress placed on the cable insulation), whilst the direct current is maintained constant.

Following the step reduction, the direct voltage is then ramped back up to the rated voltage whilst the direct current is ramped down, such that, following the initial step, the direct power is maintained constant. In such systems, the magnitude of the step in direct voltage is often approximately 20%.

Whilst this method partly alleviates the thermal stress on the cable, the reactors, valves, transformer, etc, it is not appropriate for a rapidly changing power demand.

For example, when interconnecting a generating source which is peripatetic in nature, the source covering the extremes of the direct current transmission system rating, the above-described control method of selecting the operating direct voltage and direct current is inappropriate.

This is because frequent and possibly rapid changes in generation, as may be found with renewable sources of energy, for example wind generation, will result in problems associated with such operation, including, but not limited to:

- Thermal stressing of the power transmission medium;
- Thermal stressing of the converter equipment;
- Large variation in converter reactive power absorption; and
- An inability to operate in the steady-state at or near to zero power transfer.

According to the invention, there is provided a control method for a direct current power transmission system, the method including the step of altering direct current and direct voltage simultaneously in response to fluctuations in power demand.

The method may further include the step of altering the direct current and direct voltage such that the net reactive power absorbed at each converter (where the system includes a number thereof) remains approximately constant.

By maintaining approximately constant reactive power, the variation in the magnitude of direct current is kept relatively small, only reducing by approximately one half, over the entire power range of the converter.

By minimising the variation in the magnitude of direct current over the entire operating range of the converter, the thermal cycling effect on main circuit plant, such as transmission conductors, reactors, thyristor valves, converter transformers etc, is minimised.

Reducing the steady-state direct voltage below 1.0pu (where pu indicates rated voltage) for any change of power demand reduces the electrical stress on cable insulation and hence prolongs the operational life of the cable.

As the reactive power consumed at each converter station remains constant, the need to switch shunt reactive power elements with the changing load is obviated.

Zero power transfer is achieved by forcing the average DC voltage to zero, leaving the direct current at a higher value. Thus the risk of discontinuous current is avoided.

Reducing the direct voltage reduces lag times due to charging/discharging of the cable, thus improving the response time of the converter to changes in power demand around zero.

Reducing cable charging/discharging time (reduced control lays) improves control stability around zero power transfer.

At low power, increased inverter operating angles reduce the risk of commutation failure.

The invention is concerned with the selection of the appropriate value of direct voltage and direct current to achieve a particular value of power transfer whilst minimising the electrical stress on main circuit equipment in the event of continuously changing, and even reversing, energy transmission.

The invention involves the selection of steady-state values of direct current and direct voltage in order to meet a certain level of power transmission whilst maintaining the reactive power absorbed by the converters to an approximately constant value between rated power transmission and zero power transmission. This results in a reduced variation in the direct current, approximately a change of the order of two to one, and hence minimises the thermal cycling on electrical plant.

The method of selecting the appropriate values of direct voltage and direct current are based on calculating the reactive power absorption of the converter at rated power.

The direct voltage and direct current for a transmission system are conventionally based on an economic analysis of the capital cost of the transmission media versus the cost of losses. The control method of the invention uses the same basis to establish the rated conditions.

The rated operating condition defines the converter absorption based on classical converter equations. By iterative calculation for power transmission levels below rated power, a combination of direct voltage and direct current can be found that for a given power transfer level cause the converter to absorb approximately constant reactive power. An expression can then be developed relating the appropriate direct voltage, found through the iterative calculations, to the power transfer level. This equation normally takes the form of a quadratic equation and is particular to each application.

In order to speed up the response to load changes, a first station may be made the direct voltage control point while a second station, at an opposite end of the DC link to the first station, is made the direct current control point, irrespective of power direction.

Hence, at around zero power where the direct voltage control slope is greatest and where the direct voltage can slip between positive and negative, there are no telecommunication delays in the direct current pole response. On the other hand, the slope of the direct current is low at around zero power and hence changes to the direct current can be allowed to have a slower response.

At the first station the direct voltage is controlled by:

a) firing angle regulation; and

b) tap-changer control to maintain the valve winding voltage to within a limited steady-state range.

At the second station the direct current is controlled by:

a) firing angle regulation; and

b) tap-changer control to maintain the valve winding voltage to within a limited steady-state range.

Control of the variable quantity is achieved by continuous variation of the converter firing angle with changing system conditions. Should the measured valve winding voltage go outside of the band defined as the steady-state range then converter transformer tap-changer action will be involved, increasing or decreasing the converter transformer valve winding voltage as appropriate and hence returning the converter firing angle to within the steady-state range.

According to the invention, there is also provided a direct current power transmission system comprising a first AC system connected by an AC/DC converter to a DC link, the DC link being connected to a second AC system by a DC/AC converter, the converters having respective first and second control systems, the control systems being operable to alter simultaneously direct current and direct voltage in response to fluctuations in power demand.

The control systems may be operable to alter direct current and direct voltage such that the net reactive power absorbed at each converter remains approximately constant.

The first controller may be operable to control direct voltage and the second controller may be operable to control direct current.

In order that the invention may more readily be understood, a description is now given, by way of example only, reference being made to the accompanying drawings, in which:-

Figure 1 is a schematic diagram of a conventional HVDC (high voltage direct current) transmission system;

Figure 2 is a graph showing simplified static characteristics of a control system in a conventional HVDC system;

Figure 3 is a graph showing the static characteristics of a control system in a HVDC system according to the invention.

Figure 1 shows a conventional HVDC system connecting two AC systems 10, 20.

The system consists of two HVDC converters 12, 22, their associated transformers 18, 28 and AC filters 14, 24, which also provide reactive power support.

The converters 12, 22 are constructed using valves (not shown), which are themselves constructed from series- or parallel-connected electronic switches. The number of electronic switches used depends upon the DC transmission current and voltage. The most commonly used switch is the thyristor. The converters include bridges of the “graetz” 6-pulse bridge topology, and are in a 12-pulse configuration constructed out of two phase-shifted 6-pulse bridges.

To allow the converters 12, 22 to transfer power requires control of the turn on, or firing, of the thyristor valves. This is accomplished using a converter control system 16, 26, described below.

The connection between the two converters 12, 22 consists of either a transmission line or cable 50, or a combination of the two, and may also include DC reactors and filters.

Power can be transferred in either direction between AC systems 10, 20. Whatever the power direction, the direct current direction is dictated by the polarity of the thyristors in the HVDC valve. Reversing the power flow along the DC link is accomplished by changing the operating firing angle of the converters 12, 22 and reversing the direct voltage. The converter supplying the DC power to the DC system is called the rectifier and the converter taking power from the DC system is called the inverter.

Each converter 12, 22 in the HVDC system has its own control system 16, 26. The individual control modes of each control system 16, 26 are known as its static or station characteristics.

The static characteristics are commonly shown as two-dimensional drawings on a common graph with direct voltage and current as the axes.

Figure 2 shows the simplified static characteristics of the conventional HVDC system of Figure 1.

The rectifier normally operates on constant DC current control (for example line B_1-C_1) while the inverter typically operates in either constant extinction angle (or V_{DC}) (line Y-Z). Other control characteristics are included to modify the converter operation during system transients.

The intercept of these two characteristics gives the operating point of the system (OP). Changes in transmitted power are achieved simply by changing the ordered DC current, I_{order} (for example B_2C_2 gives OP_2).

Reversing the power transfer requires the two control systems to change their respective firing angles and to reverse the direct voltage. Typically this is first done by lowering the transferred current to a minimum value, for example OP_1, and shutting down (blocking) the converters. The converters are then started up (deblocked) with the appropriate control firing angles to give minimum current with the opposite direct voltage (OP_3). This requires the discharging and recharging of the DC cable.

This has several disadvantages, namely:-

- increased voltage stresses on the DC cable and other equipment;
- increased control time lags which can adversely affect the control system response;
- increased switching activity on AC system reactive elements;
- voltage transients in either or both AC systems; and
- operation at low power is with low current, which may be discontinuous leading to increased AC system harmonics and increased valve switching losses.

Figure 3 shows the static characteristics of a control system in a HVDC system according to the invention.

According to the invention, one of the converters 12, 22, which in this embodiment is converter 22, is always in constant reactive power control. That is, it maintains its reactive power exchange with its respective system at a constant value. It also has other characteristics such as constant DC current and voltage characteristics to form limits under transient conditions.

The other converter 12, 22, which in this embodiment is converter 12, is in either constant DC voltage control, constant DC power control or constant frequency control. In practice it is possible to be in a combination of all of the above. For example, where the DC voltage order is derived from an outer control loop which is measuring and controlling AC system frequency, the converter 12 is in constant DC voltage control. Although the example is for a constant power control, it could be for a constant frequency control as DC power is proportional to AC system frequency. Other characteristics such as a DC current or reactive power limit are present for transient conditions.

Example 1

In a first exemplary scenario, converter 12 demands that its characteristic intercepts with that of converter 22 at operating point OP_2. If the frequency of AC system 10 decreases, then the constant frequency characteristic moves such that the intercept now moves to OP_3 and the power transmission is reduced, but AC system 10 maintains constant AC system frequency.

The reduced DC power transfer is achieved by changes in both the direct current and voltage.

Further decreases in DC power (if necessary to zero) are achieved simply by moving the intercept to OP_4.

Should power reversal be required (due to further attempted reductions in the frequency of AC system 10) then the characteristic is lowered still further until intercept at OP_5 or OP_6 is achieved.

Under these conditions power transfer on the link has reversed; power will flow into AC system 10 to maintain its frequency constant. The reversal of the DC voltage is achieved gradually and linearly, thus avoiding rapid charging and discharging of the DC cable.

In addition, the avoidance of blocking and the changes to the two converters reactive power consumption means that voltage transients are avoided in either AC system.

CLAIMS

1. A control method for a direct current power transmission system, the method including the step of altering direct current and direct voltage simultaneously in response to fluctuations in power demand.

2. The method of Claim 1 wherein the system includes a number of converters, the method further including the step of altering the direct current and direct voltage such that the net reactive power absorbed at each converter remains approximately constant.

3. The method of Claim 1 or 2 wherein the direct voltage is controlled by a first control system and the direct current is controlled at a second control system, the first and second control systems being at opposite ends of a DC link.

4. A direct current power transmission system comprising a first AC system connected by an AC/DC converter to a DC link, the DC link being connected to a second AC system by a DC/AC converter, the converters having respective first and second control systems, the control systems being operable to alter simultaneously direct current and direct voltage in response to fluctuations in power demand.

5. The system of Claim 4 wherein the control systems are operable to alter direct current and direct voltage such that the net reactive power absorbed at each converter remains approximately constant.

6. The system of Claim 4 or 5 wherein the first controller is operable to control direct voltage and the second controller is operable to control direct current.

7. A system substantially as herein before described with reference to, and/or as illustrated in, any one or more of Figures 1 and 3 of the accompanying drawings.

8. A method substantially as herein before described with reference to, and/or as illustrated in, any one or more of Figures 1 and 3 of the accompanying drawings.

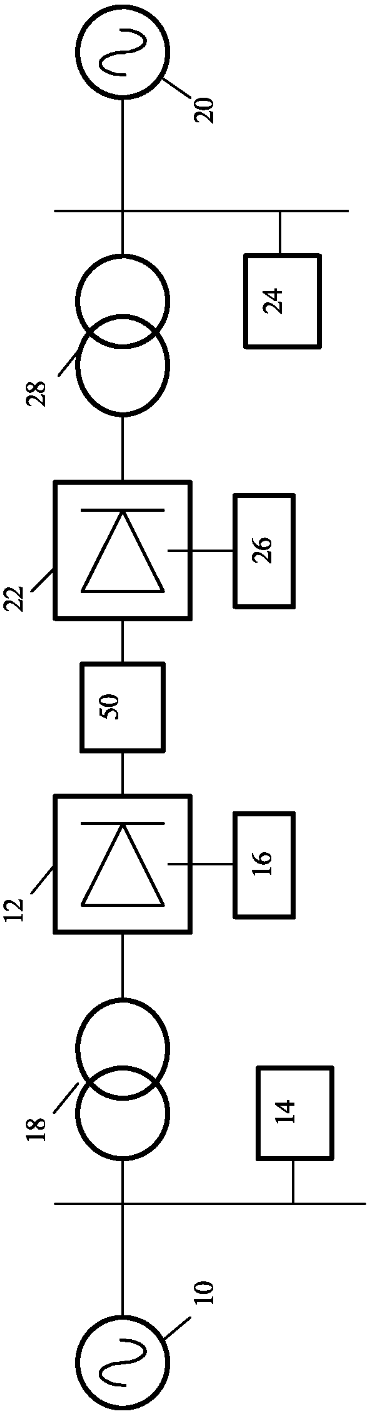
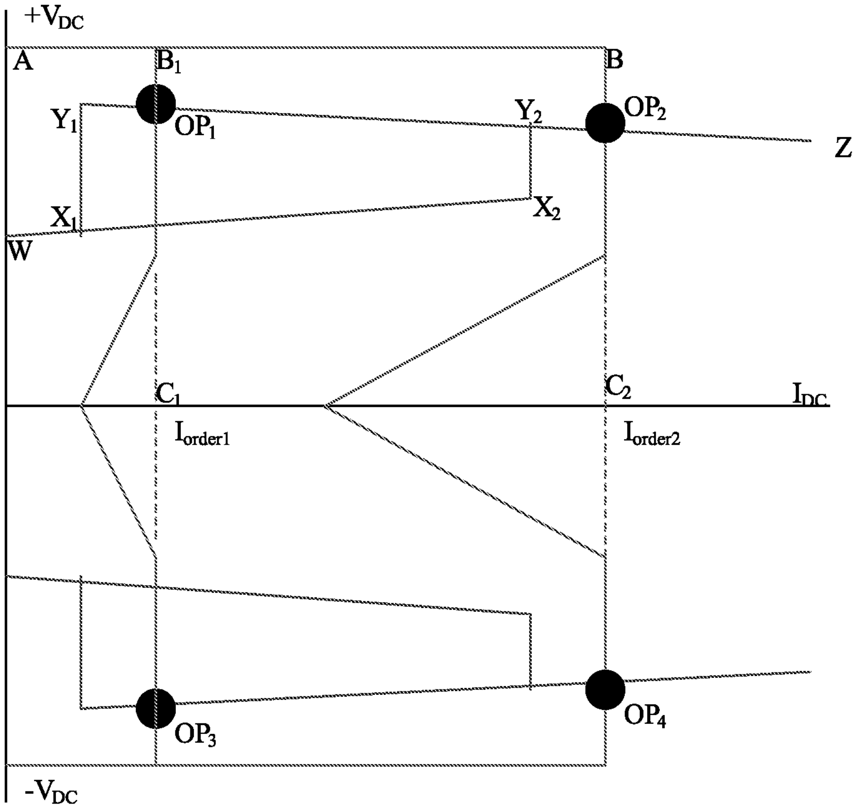


FIG. 1


+V_{DC}
A
B_1
B
Y_1
OP_1
Y_2
OP_2
Z
X_1
X_2
W
C_1
C_2
I_{DC}
I_{order1}
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OP_3
OP_4
-V_{DC}

FIG. 2

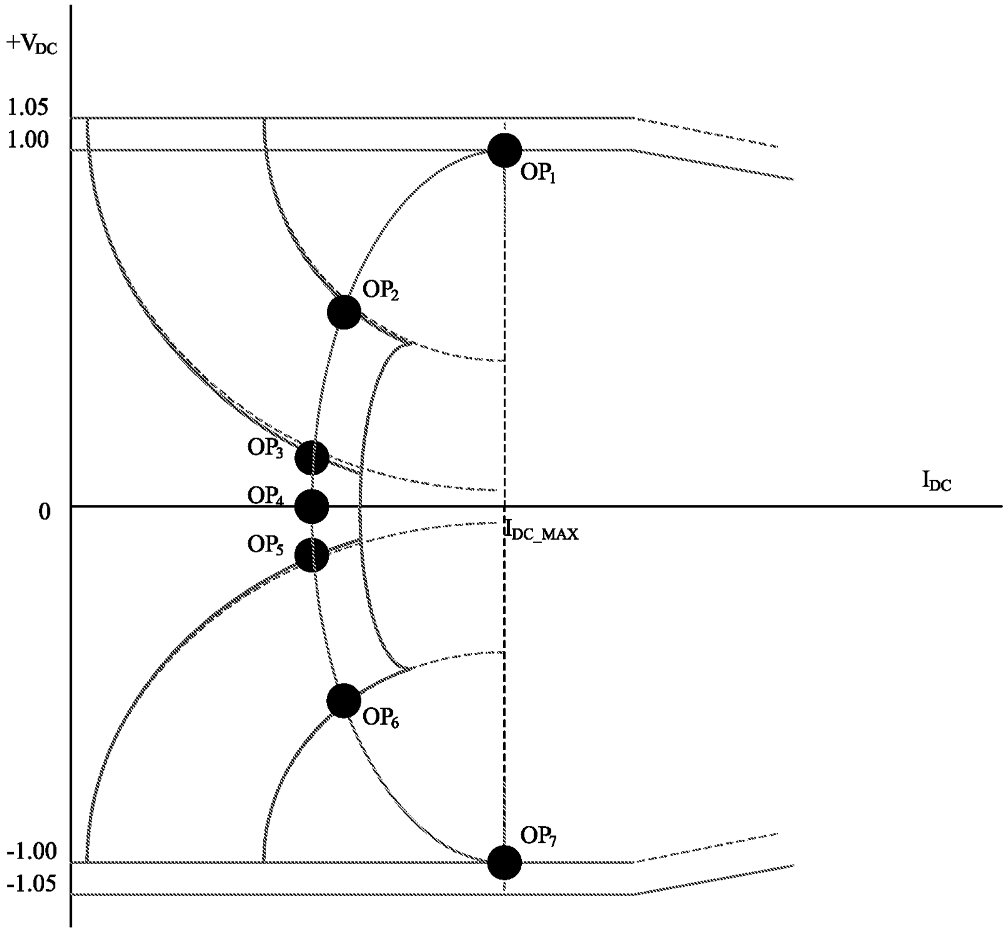

FIG. 3