Control of Voltage Source Converters in Wind Farm Based Multi-Terminal HVDC Transmission Systems

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Abstract–**This paper describes a control technique for control of voltage source converters (VSCs) in the multi-terminal high voltage direct current (HVDC) transmission systems. The proposed control technique is based on a multi-loop current and voltage control scheme for tracking the reference value of the DC link voltage in the rectifier side to achieve a proper performance during the irregular circumstances of wind farm operation. In addition, the proposed control scheme is able to transmit the maximum power to the consumption sectors. Moreover, the proposed control method on the grid side converter guarantees least amount of current harmonics injection into the AC power grid. The MATLAB simulation results are presented to confirm the effectiveness of the proposed control technique for variation in AC voltage amplitude and frequency of wind turbines output voltage.**

Index Terms–**Wind farms; multi-terminal; high voltage direct current; power quality.**

I. INTRODUCTION

Energy consumption is ever increasing and over the past decades, the increment in energy demand has been highly balanced by capacity development of conventional power sources. But, a further electricity generation to balance energy consumption is considered by unsustainable energy sources, especially due to limited source of their primary energies and due to negative impacts they introduce into the environment. In order to supply the future electricity demand as well as to replace ageing existing generations, a number of new generation technologies based on the renewable energy sources e.g. wind and solar have been developed. In European countries, development of wind power plants is growing fast for electricity generation; but still a small percentage of the energy demand is supplied by contribution of wind power sources.

With the purpose of integrating the future far offshore wind farm power plants into the power grid and, regarding the capacity of these plants, long transmission lines with higher capacity would be essential. But, variable wind speeds and linked generated power would result in a low capacity factor of the transmission and consequently relatively high transmission cost per amount of energy delivered. This capacity factor will be increased by connection of multi offshore wind power plants into the transmission lines. Furthermore, if the transmission is extended more, it can be used to smooth power trading between different societies as well as evacuate power from the wind power plant. If we consider these solutions, multiple offshore wind farms would be integrated to multiple onshore power grids and consequently it would lead to the development of a transnational offshore network.

High-voltage direct-current (HVDC) transmission technology can be considered as a suitable alternative for such a multi-terminal offshore network, where huge amount of power can be transmitted over a long distance. Furthermore, because the offshore network can act as a power pool where power can be injected to and extracted from the network at different nodes, control of direction of power during maintaining voltage in the network is needed. Implementation of voltage source converter HVDC (VSC-HVDC) technology is a constructive solution for changing the direction of power while maintaining voltage in the DC network. In addition, an independent control for active and reactive power can be performed.

A number of control strategies have been proposed in the literature for operation of a multi-terminal VSC-HVDC network, e.g., Combined and coordinated control [7], current margin control [8], voltage margin control [9], and AC-side voltage control [10]. However, the weakness and lack of strong regulatory system has been sensed to guarantee the generation of safe and stable DC voltage in the side of HVDC transmission lines.

A control technique is presented in this paper for tracking the reference value of the DC link voltage in order to achieve a stable DC voltage for connecting to the long transmission system based on multi-terminal HVDC system. By application of the proposed control technique, maximum available power will be injected through an interfaced VSC-HVDC to the power grid.

The rest of the paper is organized into three sections. Following the introduction, the general schematic diagram of a multi-terminal DC system with three terminals as a case study, and control of wind farm side and grid side converters under different conditions will be introduced in section III. Moreover, simulation results have been performed to demonstrate the efficiency and applicability of the developed control strategy in Section IV. Finally, conclusions are drawn in Section V.

The reset of the paper is organized as follows. Section II describes different parameters of a three terminal HVDC system and control of wind farm side and grid side converters under different conditions. MATLAB simulation results are presented in Section III for different conditions of wind farm applications and grid conditions. Finally, conclusions are drawn in Section IV.

II. HVDC STRUCTURE AND CONTROL OF CONVERTERS

Fig. 1 shows the block diagram of a three terminal HVDC system based on VSCs, which are connected to the AC grid. This system includes two wind farm terminals and a terminal connected to the power grid.

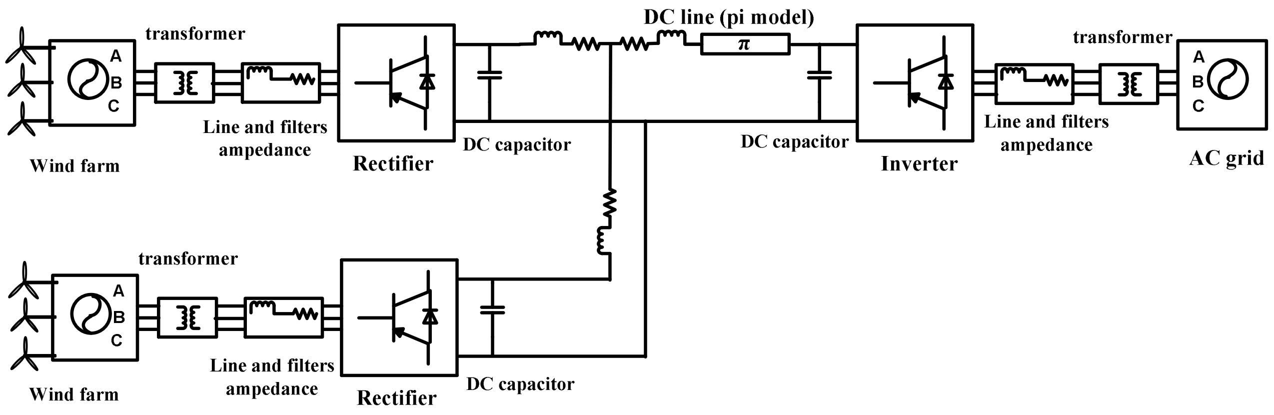


Fig. 1. Three terminal HVDC model.

Since the variable wind power is the input driving force of turbines, the output voltage of wind turbines is in the form of unregulated AC with variations in both amplitude and frequency. A control system must have the capability to regulate the output voltage in a predetermined reference during mentioned variations. As the terminals in HVDC structure are located in different places and they use various amount of wind energy, the control system should help each terminal to deliver constant DC voltage; then, this voltage would be converted from DC to AC in the grid side converter to produce regular and stable AC voltage.

A. DC link voltage regulation

As shown in Fig .2, the principle of this control method is based on different control loops. Each inner loop includes a series of reference values, which are specified by the designer or other loops. The output production of the outer control loop is the reference voltage to generate the switching pattern for the power electronic converters.

DC link voltage is compared with its reference value and regulated via PI controller to generate reference value of i_d. This current obtains the inputs for the current controller to generate reference voltages for the converter.

From Fig .2 and neglecting resistance of line impedance, AC voltage of the converter can be calculated as:

$$V = L\frac{di}{dt} + u \tag{1}$$

Rewriting (1) in the Laplace domain leads to:

$$V = sLi + u \tag{2}$$

where v is the voltage at the common bus, L is the leakage inductance of the phase reactor, i is the current flowing at the AC side of the converter, u is the voltage generated by the converter and s is the Laplace operator.

Transforming (2) to the *dq* components results in:

$$V_d = sLi_d - \omega Li_q + u_d \tag{3}$$

$$V_q = sLi_q + \omega Li_d + u_q \tag{4}$$

where, ωLi_q and ωLi_d leads to a cross coupling between d and q axis quantities which makes the independent control of active power more complex. In other words, when i_q is regulated to control the reactive power, V_d will be altered, and thus, the active power will also change. In order to eliminate the cross coupling, V_d and ωLi_q are fed forward on the d-axis controller while V_q and ωLi_d are fed forward on the q-axis controller.

The voltage reference values are then transformed to the *abc* quantities and $V_{d\text{-}ref}$ and $V_{q\text{-}ref}$ are fed as inputs to the controlled voltage source.

B. Control of the HVDC converter in the consumption side

After DC link voltage regulation, the control method should be able to transmit the maximum input active power to the grid. Also, it should inject the least amount of current harmonics in to the consumers and grid.

In order to be able to control the active and reactive power independently, the control scheme implemented on the grid side VSC is developed based on the vector control method.

The active and reactive power exchanged at the common bus can be calculated as:

$$P = V_a i_a + V_b i_b + V_c i_c \tag{5}$$

$$Q = \frac{1}{\sqrt{3}}\left(V_{ab} i_c + V_{bc} i_a + V_{ca} i_b\right) \tag{6}$$

where, Va, Vb, and Vc are three phase phase voltage at the common bus and i_a , i_b, i_c are three phase currents flowing at the ac side of the converter Transforming (5) and (6) to the *dq0* components and writing the results in pu of the converter rated capacity leads to:

$$P = V_d i_d + V_q i_q + 2V_0 i_0 \tag{7}$$

$$Q = V_q i_d - V_d i_q \tag{8}$$

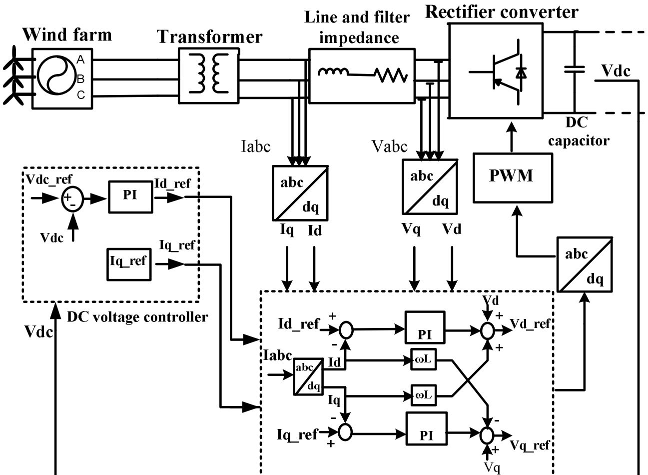


Fig. 2. Diagram of wind farm side controller loops.

C. Connection to the stable grid.

For a balanced three phase system, the *0* components are equal to zero. Moreover, by considering V_d aligned in phase with V_a, V_q is zero. Therefore, (7) and (8) can be rewritten as:

$$P = V_d i_d \tag{9}$$

$$Q = -V_d i_q \tag{10}$$

It can be seen that the active and reactive powers can be controlled independent of each other by regulating i_d and i_q.

The grid frequency should be sampled by the PLL block. Three-phase grid currents should be transformed from abc to 0dq in this frequency according to the equation (11). Then, these currents are compared with their references, which can be calculated from (9) and (10). The error values are regulated through PI controllers and then, transformed to the abc frame in order to produce voltage references for PWM block. Schematic diagram of this control is depicted in Fig .3.

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta) & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin(\theta) & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} . \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{11}$$

D. Grid connection and unbalanced load compensation.

Fig. 4 shows a multi-terminal HVDC system connected to the AC grid in which an unbalanced nonlinear load is connected to the point of common coupling (PCC). This load may causes instability in the grid side current by producing an unbalance nonlinear current. After connection of multi-terminal HVDC to the PCC, it can supply the grid and load power as well as improving the power quality. It means that, in addition to perform as an independent DG, it also acts as an active power filter (APF) to improve the power factor and total harmonic distortion (THD). In this particular case, the control method should work as the following way to comply the required performance of multi-terminal HVDC system. According to Fig .4, harmonic injection and active power injection blocks are used to prepare required current references for power converter. A hysteresis band current control (HBCC) is used to obtain switching pulses of the converter. According to (9) and (10),it can be concluded that current reference of grid side converter have to be considered as q- component of load current in order to compensate load reactive power. Therefore:

$$i_q^* = i_{lq} \tag{12}$$

Active power transfer should also be done by HVDC system based on the following equation for the d-component of reference current.

$$i_{d-h1}^* = \frac{P_{ref}}{V_d} \tag{13}$$

This equation generates reference current at fundamental frequency. P_{ref} is the active reference power for HVDC system and V_d is the d-component of the PCC voltage. According to Fig .4, the reference current for HBCC block is a combination of harmonic currents and fundamental currents as:

$$i_{tot}^* = i_{h1} + i_{\tilde{h}} \tag{14}$$

In order to have harmonic compensation capability, $i_{\tilde{h}}$ have to be determined by harmonic injection block. The load current should be transformed from abc to αβ reference frame by (15).

As shown in Fig. 5, this current entered into the self-tune filter (STF) to extract the desired harmonic frequency and is defined in its predetermined set point frequency [11, 12].

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ 0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} . \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{15}$$

where $\boldsymbol{\omega}_n$ is the set point frequency of the desired harmonics and K is the gain coefficient of the STF which have to be smaller to increase the accuracy of harmonic extraction. By setting the $\boldsymbol{\omega}_n$ in the fundamental frequency (50 Hz) and subtracting the output of STF from its input ($\hat{i}_{\alpha\beta}$), remaining harmonics can be achieved. These harmonics have to be injected into the grid by VSC to act as an APF. By entering these amounts to the HBCC and compare them with the actual values, the ideal switching pattern would be generated for correct operation of converter. Fig. 6 shows the main principle of HBCC in which the actual current is compared with reference current. Upper and lower bands are considered around the current. When current passes upper and lower bands, converter leg switches changes in such a way to bring the current back between band by changing the leg voltage polarity[13]-[15].

III. SIMULATION ANALYSIS

Table 1 shows simulation parameters for a three terminal HVDC of Fig .1 in which two wind farms are connected to a DC line and the power is transferred to AC grid and an unbalanced nonlinear industrial load. Two following scenarios are considered for the simulation analysis in this study.

A. Control of WFSVSC

At first, variations of the wind farm for both voltage magnitude and frequency is examined. Fig. 7 shows reaction of the proposed control method to the variations of wind farm under four worst case scenarios for frequency and magnitude changes. These scenarios may seems to be unrealistic but performance of the WFSVSC and its control strategy to regulate the voltage under different circumstances can be verified in sever conditions. As depicted in figures, V_{abc1} and V_{abc2} are the output voltage of wind turbines 1 and 2 respectively. V_{dc} is the DC voltage in the output of rectifier and V_{dc-ref} is the DC voltage in the input of converter after passing from DC line. The objective is to maintain the DC voltage in the 700 V set point voltage level.

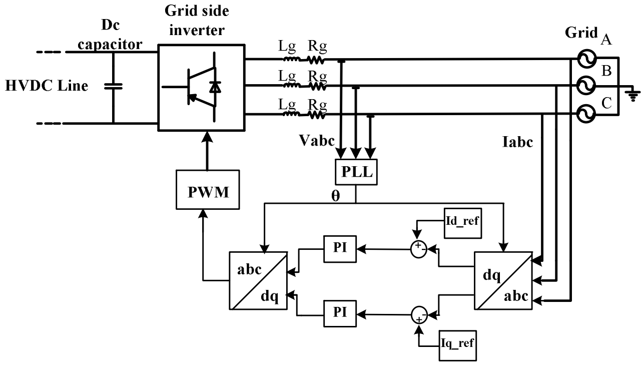


Fig. 3. Schematic Diagram of grid side control.

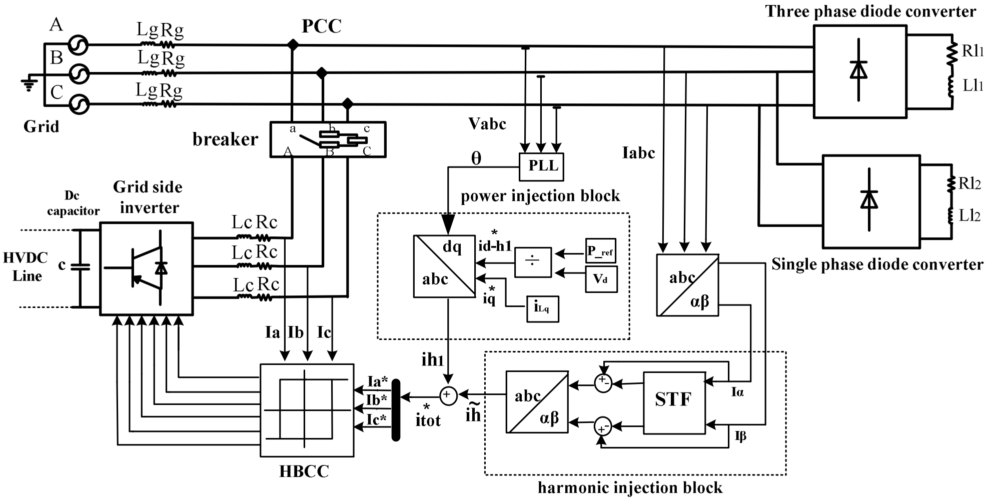


Fig. 4. Schematic diagram of grid side control during connection of the unbalanced nonlinear load.

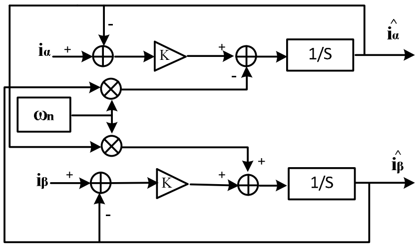
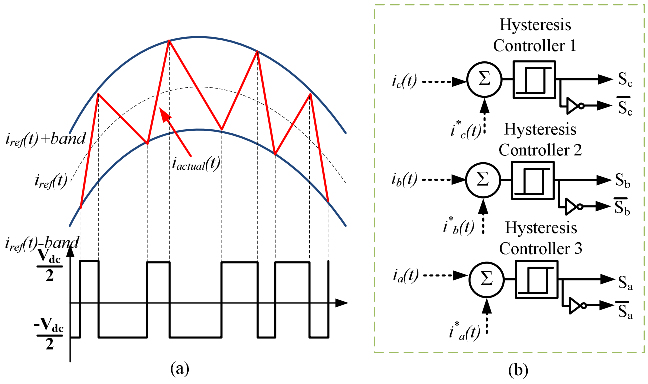


Fig. 5. Diagram of the Self-Tune Filter (STF).



(a)

(b)

Fig. 6 (a). Reference current, upper and lower bands in HBCC and generated voltage, (b) HBCC with 3 separated controllers for each converter leg.

The first type of changes in Fig. 7 is the ramp type, which is the common type of changes in wind farm turbines. Changes are applied between t_1 and t_2 that are shown with dash lines. Results show that for ramp changes of WT_1 and WT_2 voltages in Fig. 7, the DC link voltage tracks its reference values. Fig. 8 shows that the DC link voltage is changed after frequency variations but transients are damped after a short time.

B. Control of GSVSC

Control scheme of GSVSC should be able to transmit the maximum input power to the grid in different situations. Grid connection on the consumption side is modeled in two forms: HVDC system connected to (1) the stable grid, and (2) the grid and an unbalanced nonlinear load at PCC. Fig. 9 shows DC link voltages of rectifier output voltage, DC link voltage of inverter input and network current and voltage. The control scheme eases synchronous connection of the HVDC system to the grid with injection of least amount of current harmonics (PF=1 and current THD less than 3%).

A three phase unbalanced nonlinear load is connected to the PCC and HVDC. In this case, the proposed control technique should connect the HVDC line to the AC grid. Fig. 10 shows HVDC, grid, and load currents before and after connection of HVDC line to AC system. As can be seen, after connection of HVDC system to AC system, the maximum power is injected to the grid, and the grid voltage and current are in phase and grid current is free of harmonic frequencies (PF=1 and THD=1.9%).

TABLE I
SIMULATION PARAMETERS

Parameters	Value
Input voltage source	3 phase, 600 V, 60 Hz
Transformer	Yg/D , 600/240 V
Interfacing resistance (R_c)	0.1mΩ/phase
Interfacing inductance (L_c)	2mH/phase
DC Capacitors (C)	37.5mF Each side
Line model	75 km model ,π
AC Grid	380 V 50 Hz
Switching/Sampling frequency (f_{sw})	3000 Hz
DC-link voltage set point ($V_{dc\text{-}ref}$)	700 V
Grid resistance (R_g)	0.1mΩ Per phase
Grid inductance (L_g)	5 mH Per phase
Three phase diode converter load1	R=30Ω and l= 20mH
Single phase diode converter load2	R=20Ω and l= 20mH

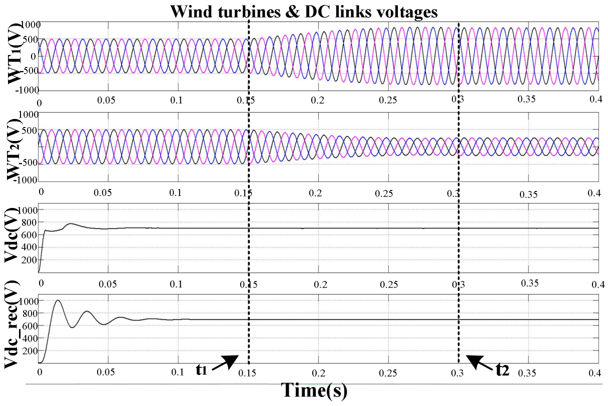


Fig. 7. Ramp type variation of the wind turbines voltages.

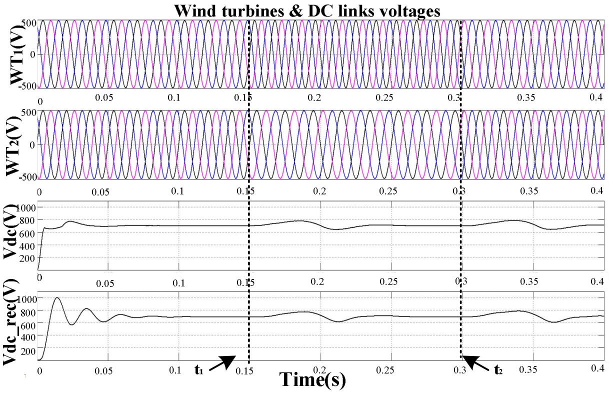


Fig. 8. Step type frequency variation by 10 Hz increment (decrement) for WT_1 (WT_2).

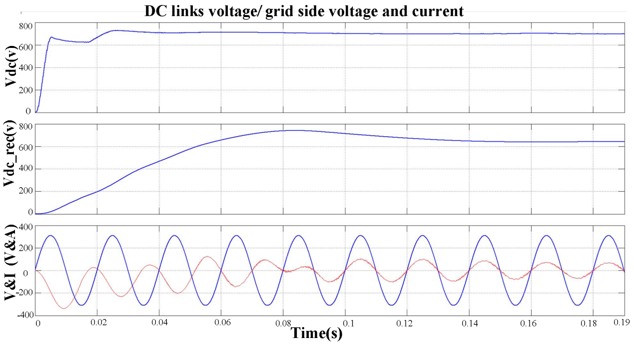


Fig. 9. Connection to the stable grid.

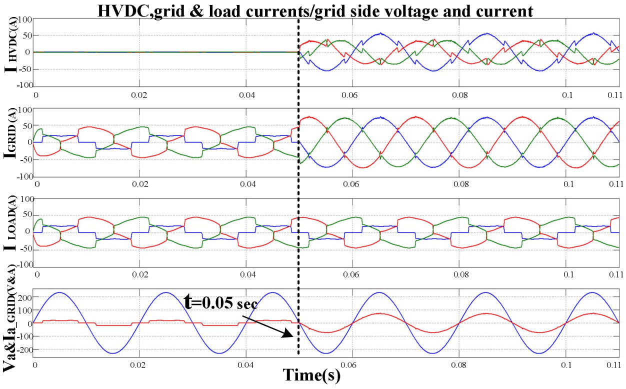


Fig. 10. Connection to the grid and unbalanced nonlinear load.

IV. CONCLUSIONS

This paper presented a control method for controlling voltage source converters in wind farms based multi-terminal HVDC systems. Due to inherent variations of output voltage in wind turbine generators in terms of amplitude and frequency, the proposed control method had the ability to control the interfaced converters to provide a constant DC link voltage. Different types of variation were simulated. The results confirmed the ability of the proposed control strategy to regulate the DC link voltage. The proposed control strategy was also investigated for controlling interfaced converters between HVDC line and AC systems during the connection of unbalanced nonlinear loads into the AC grid. Simulation results confirmed that by using the proposed control technique, the interfaced converter can compensate unbalanced and nonlinear current components, thus guaranteeing a balanced three phase currents for utility grid.

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