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DETERMINING THE BEST SUITABLE CONTROL STRATEGY OF THE VSC-HVDC FOR VOLTAGE STABILITY

ABSTRACT

In this paper, to improve voltage stability of the most critical bus of the New England 39 bus test system has proposed a new DC transmission line based on the VSC-HVDC (Voltage source converter-High Voltage Direct Current) instead of AC transmission line. The power transferred has been provided by the VSC-HVDC that have two steady state control modes to the critical bus. It is determined by the sensitivity analysis the most critical bus of the power system. In this bus the effect of heavy loading on long term voltage stability is investigated. In the modified test system for all situations, to improve of the voltage stability is determined the best suitable control strategy for the voltage source converters. Simulations are conducted in DIgSILENT Power Factory 15.0 software. The results of proposed test system compared and presented the base system that included AC transmission line.

Keywords: Voltage Stability, VSC-HVDC, VSC Control Strategy, P-V Curves, DIgSILENT

1. INTRODUCTION

Due to economical reasons, power systems today work closer to their operating limits and it makes the blackouts more likely to happen. Many of the recent large blackouts were the consequence of voltage collapses [1 and 2]. So, for the last decades voltage stability has been a big concern for power system planning and operation [3]. The improvement of the stability margins in power system when using VSC-HVDC has made of this technology an important option among grid owners when there is a need for increasing the transmission capacity of the network [4]. Furthermore, VSC-HVDC links are recently utilized to module the power flow in power systems to improve the long-term voltage stability [5 and 6]. Especially, in weak AC networks, to improve voltage stability using VSC-HVDC systems has been proposed by many researchers. Therefore, in the past decades, the problem associated with HVDC converters connected to weak AC networks has become an important research field. In [4], a comparison study is conducted to investigate the long-term voltage stability improvement once either a new ac transmission line or a VSC-HVDC link is connected to the grid. In [7 and 8] VSC-HVDC capability to improve long term voltage stability once VSCs hit their current limit is investigated. The classical PV curves are used for investigation. In [9], singular value sensitivity is applied to reach the optimal control of embedded VSC-HVDC for improving the steady-state voltage stability. In both [7 and 9] the dynamic simulation is not included which is important when performing realistic analysis of the voltage stability problem. At

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present, there are two main types of power flow algorithms for AC/DC systems, sequential iterative method [10 and 11] and integrated iterative method [12 and 13]. In [14], the PV and QV curves were used to investigate voltage stability of a weak two area AC network. Though many methods for voltage stability analysis of AC/DC systems with VSC-HVDC have been proposed in different ways, few papers carefully consider the influence induced by different control modes of VSC-HVDC, which actually plays an important role on the voltage stability of the AC/DC systems. The voltage stability of AC/DC systems certainly has an importance for control of VSC-HVDC systems, especially if the connected AC system is weak. For example, a VSC-HVDC link has two feasible operation modes, i.e., alternating-voltage control or reactive-power control. A basic question is: which operation mode gives the greatest stability margin [15]. Our main aim in this paper, at an AC network that 39 Bus New England test system to improve of the long-term voltage stability is determined the best suitable control strategy for the voltage source converters. Firstly, the best critical buses of the test system have determined using by sensitivity analysis. Then instead of AC transmission line to connected critical bus a new DC link has proposed and compared two different control modes for VSC-HVDC. DIgSILENT PowerFactory [16], an advanced power system simulation software package, is used for the modeling and simulations. The rest of the paper is organized as follows. In Section 2, controller structure and control modes of AC/DC systems with VSC-HVDC are presented. Section 3 explains briefly some basic concepts of voltage stability and sensitivity analysis. In Section 4, the model and method explained in section 3 are applied to the modified 39 bus New England test system with VSC-HVDC and results presented table and graphics. Finally, in Section 5, the paper is completed with a conclusion.

2. RESEARCH SIGNIFICANCE

In terms of voltage stability, the most critical bus of the 39-bus test system was determined by sensitivity analysis. The determined critical bus power transfer was carried out with High Voltage DC transmission line instead of AC transmission line. The proposed new HVDC line converters provide power transfer in two separate modes (Active power-AC voltage) and (DC voltage-AC voltage). To improve the stability of the critical bar voltage, these two modes were compared, and the most appropriate control strategy was determined. The findings of this study will contribute to control strategy and methodology for HVDC transmission lines and converters.

3. VSC-HVDC SYSTEM

In this section, the topology of the investigated VSC-HVDC is discussed. Design considerations and modeling aspects of the VSC-HVDC are given. The topology selection for the VSC-HVDC is based on the desired capabilities.

3.1. System Description

The main function of the VSC-HVDC is to transmit constant DC power from the rectifier to the inverter. As shown in Figure 1, it consists of dc-link capacitors C_{dc}, two converters, passive high-pass filters, phase reactors, transformers and DC cable.

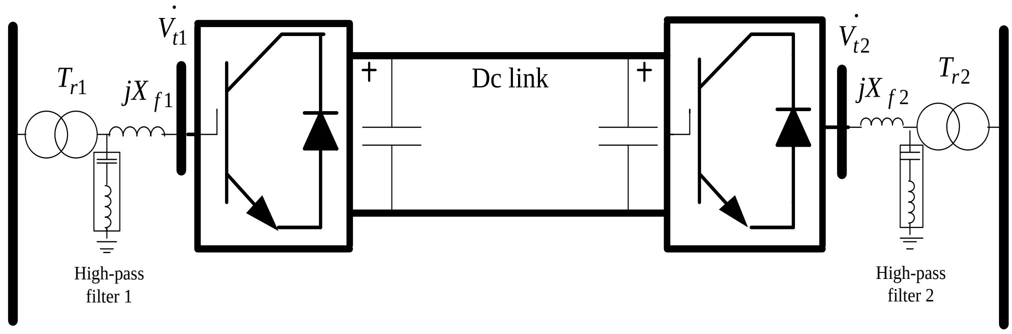

Figure 1. Topology of VSC-HVDC

The phase reactors as shown in Figure 1 are used for controlling both the active and the reactive power flow by regulating currents through them. High pass filter branches prevent the harmonics due to switching of the IGBT's from being emitted into the ac system. The dc capacitors provide a low inductive path for the turn-off current and acts as energy storage. The capacitor reduces the voltage ripple on the dc side, and the size of these capacitors depends on the required dc voltage. By using Pulse Width Modulation techniques with high switching frequency in the range of 1-2kHz, the wave shape of the converter ac voltage output can be controlled to be almost sinusoidal with the aid of high frequency filter. Changes in waveform, phase angle and magnitude can be made by changing the PWM pattern, which can be done almost instantaneously [17]. Thus, the voltage source converter can be considered as a controllable voltage source. This high controllability allows for a wide range of applications. From a system point of view VSC-HVDC acts a synchronous machine without mass that can control active and reactive power almost instantaneously. And as the generated output voltage can be virtually at any angle and amplitude with respect to the bus voltage, it is possible to control the active and reactive power flow independently.

3.2. Control of VSC-HVDC

In this paper, the control system for the VSC-HVDC system was implemented based on vector current control since it is the one which is the most well-documented and widely used today [15]. Earlier as mentioned, the VSC-HVDC can control the active and reactive power independently. The reactive power can be controlled separately in each converter by the required AC voltage or set manually. The active power flow can be controlled by the DC voltage, the variation of frequency at the AC side or set manually. This means that the active power flow, the reactive power flow, the AC voltage, the DC voltage and the frequency can be controlled when using VSC-HVDC. The control system of the VSC-HVDC is a cascade control system it typically consists of a faster vector controller. Furthermore, the vector controller is completed by additional controllers which supply the references for the vector controller. Thus, the vector controller will be the inner loop and additional controllers will be the outer loop.

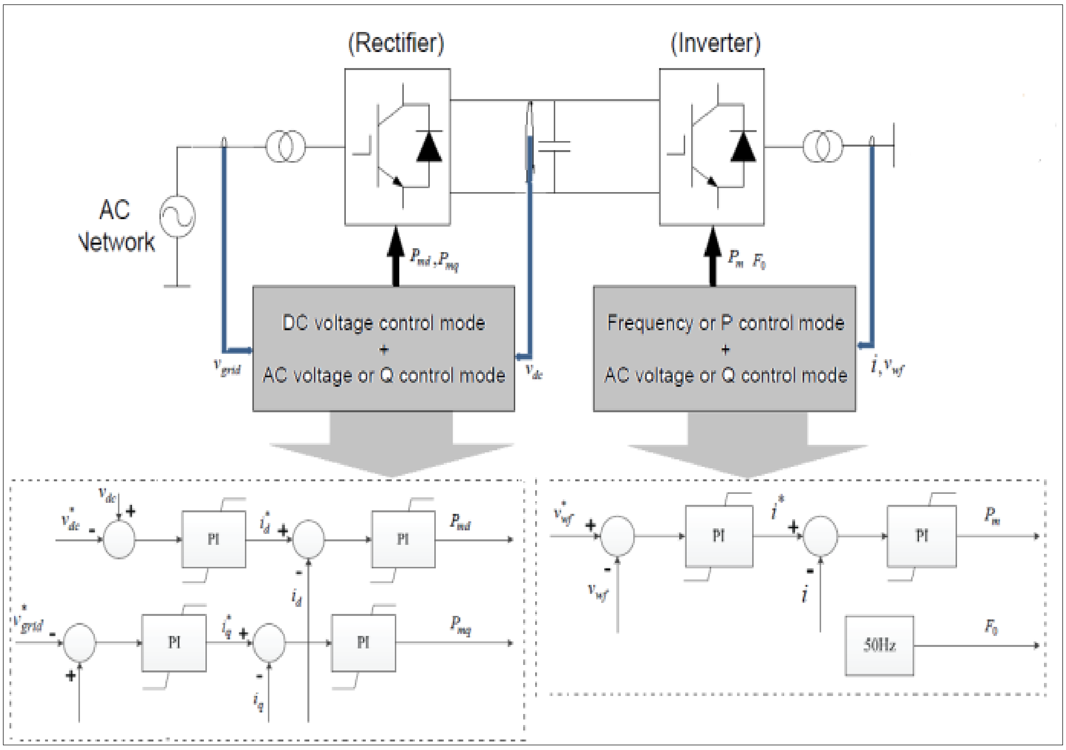

Figure 2. Overall control structure of the VSC-HVDC

In this paper the additional controllers will be referred to as the outer controllers. The outer controllers include the DC voltage controller, the AC voltage controller, the active power controller, the reactive power controller or the frequency controller. For example, as shown in Figure 2, either side of the link can choose between AC voltage controller and reactive power controller. Each of these controllers generates a reference value for the vector controller.

3.3. Vector Control

It uses the -dq synchronous reference frame to represent three-phase quantities as constant vectors in steady state [18], using PI-regulators to remove static errors in voltages and currents. The vector current control method can be formulated using the single line diagram representation of a VSC connected to a grid shown in Figure 3.

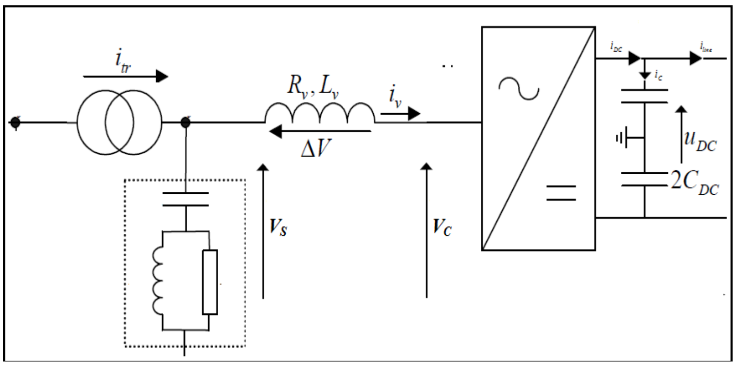

Figure 3. Single-line representation of VSC-HVDC system

3.3.1. Inner Controller

The inner control or current control loop is designed to be much faster than the outer controllers. It is not fast enough, however, to warrant neglecting its dynamics. This means current controllers and all relevant controllers higher in the hierarchy must be modeled. This control system controls the current through the phase reactor. Decoupled control is used, which means that voltages and currents are decomposed in dq-components, controlled independently [19]. The output of the current control is the desired converter voltage. The inner current controller is developed based on the following equation.

$$L_v \frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} v_{S_d} \\ v_{S_q} \end{bmatrix} - \begin{bmatrix} v_{C_d} \\ v_{C_q} \end{bmatrix} - R_v \begin{bmatrix} i_d \\ i_q \end{bmatrix} - wL_v \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \tag{1}$$

An implementation of Equation (1) is presented in Figure 4, and it shows the d and q components of current controllers of the inner current loop [20].

3.4. Outer Controller

The outer controllers are the ones responsible for providing the current references signals for the inner current controller. The terminal controller determines the behavior of the converter at the system bus [20]. In consequence, the decoupled active and reactive power control is achieved, in which the active power is controlled by the d-axis component of the converter current and the reactive power is controlled by the q-axis component of the converter current as [21].

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \frac{3}{2} i_d \begin{bmatrix} v_{S_d} \\ v_{S_q} \end{bmatrix} - \frac{3}{2} i_d \begin{bmatrix} v_{S_q} \\ -v_{S_d} \end{bmatrix} \tag{2}$$

- Active power control: determines the active power exchanged with the AC grid.
- Reactive power control: determines the reactive power exchanged with the AC grid.
- AC voltage control: Instead of controlling reactive power, AC voltage can be directly controlled, determining the voltage of the system bus.
- DC voltage control: Used to keep the DC voltage control constant.

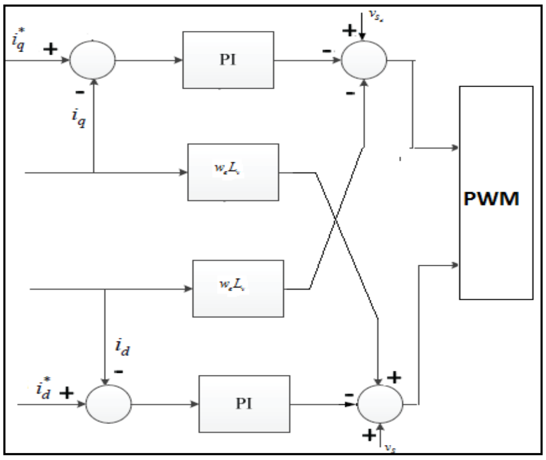

Figure 4. Structure of inner controller

The outer controllers have in common their provision of a current set point in the dq-frame for the inner current controller. Active current (id) is used to control either of active power flow or DC voltage level. Similarly, the reactive current (iq) is used to control either of reactive power flow into stiff grid connection or AC voltage support in weak grid connection. Block schemes of these controllers is presented on Figure 5. Therefore, at VSC-HVDC systems for steady-state studies many control modes can be used each VSC converter. In this paper the two control modes given by Figure 5 have been compared for voltage stability improvement.

- Constant AC active power control, constant AC voltage control
- Constant DC voltage control, constant AC voltage control

4. VOLTAGE STABILITY

In recent years voltage stability and voltage collapse phenomena have become more and more important issues in power system analysis and control. Researchers have suggested techniques for voltage stability analysis considering both static and dynamic aspects.

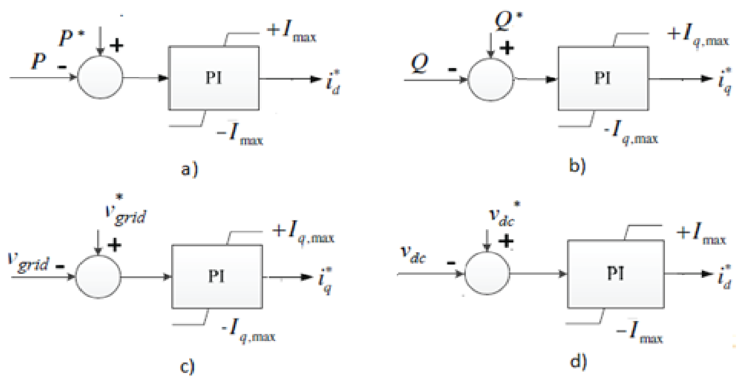

Figure 5. Outer controllers a) Controllers PI controller for active power control b) Controllers PI controller for reactive power control c) Basic scheme for AC control d) Controllers PI controller for active power control

4.1. Static Voltage Stability Analysis

The P-V Curve, Q-V Curve, have been widely used to analyze power system behaviors under varying loading conditions. Voltage stability analysis and loadability analysis are examples of the application of these curves in power system analysis. On the other hand, V-Q sensitivity analysis has been used widespread for determined of the best critical bus in weak an AC network by researchers.

4.1.1. P-V and Q-V Curves

In power flow studies and to obtain the corresponding P-V curves, the loads are typically represented as constant PQ loads with constant power factor, and increased according to

$$P_d = P_{d0}(1+\lambda) \quad (3)$$

$$Q_d = Q_{d0}(1+\lambda) \quad (4)$$

where P_{d0} and Q_{d0} are the initial real and reactive power respectively and λ is a p.u. loading factor, which represents a slow varying parameter typically used in voltage stability studies [22].

4.1.2. Sensitivity Analysis

The sensitivity analysis is applied to the power system with the purpose of determining bus number in which the most sensitive to the change in reactive power in terms of establishing voltage stability enhancement such as SVC, STATCOM, HVDC i.e devices in the best locations. The Jacobian matrix of the power system is used in sensitivity analysis [23]. The diagonal elements of the matrix represent the steady state stability indices while the diagonal elements of the inverse reduced Jacobian matrix represent the sensitivities of the bus voltages. Sensitivity analysis is applied to load buses only and positive sensitivity index indicates reduced stability margin as negative sensitivity indicates instability. The differentiation of voltage value is described as an equation of the J matrix and the variation of reactive power. $\Delta V = J_R^{-1}\Delta Q$ where $J_R = [J_4 - J_3 J_1^{-1} J_2]$ is the reduced jacobian matrix of the system?

5. CASE STUDIES

In 39 buses New England test system, instead of AC line through VSC-HVDC a new DC line that is connected to one of the most critical bus has been proposed for long term voltage stability improvement. Length of proposed DC line is 59.9km. Parameters of the proposed system which is equal to the branch power of the original AC system are given in Table 1. Design of VSC-HVDC system in DIgSilent can be seen in Figure 6. Besides, The Converter Active power (Pcon) and Converter Reactive power (Qcon) are showed power values of VSC connected to the buses that are the same of power flow values in the original system. The power transferred has been provided by the VSC-HVDC that has two steady state control modes to the critical bus. Critical buses have been determined by sensitivity analysis and results are given in Table 2. According to this table, Bus 12 has the highest sensitivity but second critical bus (Bus 28) has AC line longer than Bus 12. Therefore, in Bus 28, establishing of VSC-HVDC system has been decided. The modified IEEE 39- bus system is showed in Figure 7. In this bus the effect of heavy loading on long term voltage stability is investigated. This paper chooses the commutation bus of the buses 12, 27, 28 and 29 as the research objects.

Table 1. Sensitivity analysis results of England test system

VSC-HVDC Parameters	Typical Values
AC power and AC voltage	400MVA-150kV
DC Voltage	±100 kV
DC capacitor	1591.549 μF
Phase reactor	0.015 pu
Transformer-1	230/150kV, 500MVA, X_{tr} 8%pu
Transformer-1	150/230kV,500MVA, X_{tr} 8%pu
DC line	(0.0278ohm+0.3 ohm+3.5uS)/km

Table 2. Sensitivity analysis results of test system

Bus No	J_R	J_R^{-1}	Bus No	J_R	J_R^{-1}
12	**44.7941**	**0.0330**	13	361.0083	0.0119
28	**90.7959**	**0.0215**	3	193.9692	0.0113
27	**129.6402**	**0.0175**	17	302.0382	0.0112
9	68.9053	0.0169	11	384.0988	0.0112
1	66.5807	0.0161	5	558.7410	0.0110
26	141.4650	0.0156	20	124.4286	0.0106
7	328.4265	0.0146	10	518.8049	0.0103
8	328.4625	0.0146	6	658.8054	0.0102
15	153.3162	0.0138	23	175.1652	0.0100
18	203.1263	0.0135	15	195.5722	0.0090
21	148.5103	0.0128	16	529.2298	0.0087
29	148.2132	0.0126	22	253.2083	0.0081
14	225.7369	0.0125	19	185.0704	0.0080
4	202.2042	0.0124	2	266.1438	0.0074
24	206.1864	0.0122	-	-	-

- **The Control Mode-1:** In this control mode, the system has been controlled by converters constant AC-DC voltage [V_{AC}-V_{DC}] and constant AC voltage-active power [V_{AC}-P] in the mode. Therefore, first converter’s AC and DC voltages are setting 1.0501 p.u. and 1.00 p.u., respectively. On the other hand second converter’s AC voltage and active power parameters are 1.0499 p.u. and 350MW, respectively. These values are power flow in the original system voltages of 28 and 29 number buses besides is between this buses transferred active power. The control parameters of the converters is regulating according to power flow results. Thus, in the original system active power transferred is 350MW between bus 28 and 29. In addition to this, voltage values of these buses are 1.0501 and 1.0449 p.u., respectively. In bus 28, when active power 1702.05MW and reactive power 228.37 MVAR, power flow is not convergence and the system is in maximum loading state. In this loading point voltages of the bus 12 and the bus 27 are 0.811 p.u. and 0.86 p.u., respectively. During simulation, inverter side converter bus connected the reactive power of synchronous generator is constant and is 23.1 MVAR. The active power loss of AC system is 354.31 MW.

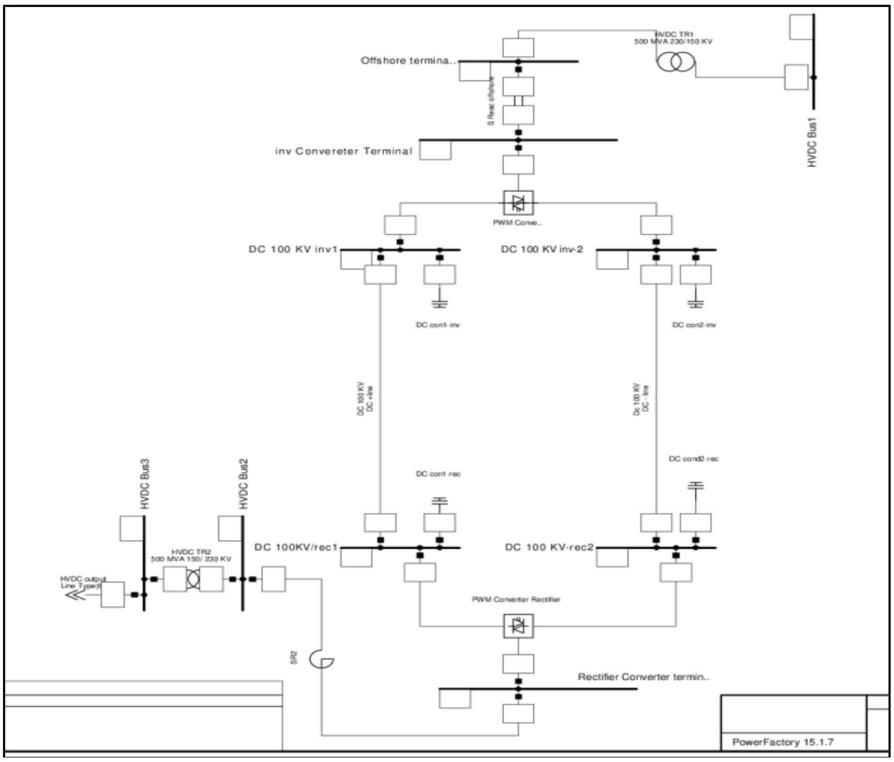

Figure 6. Implementation of VSC-HVDC in DIgSilent

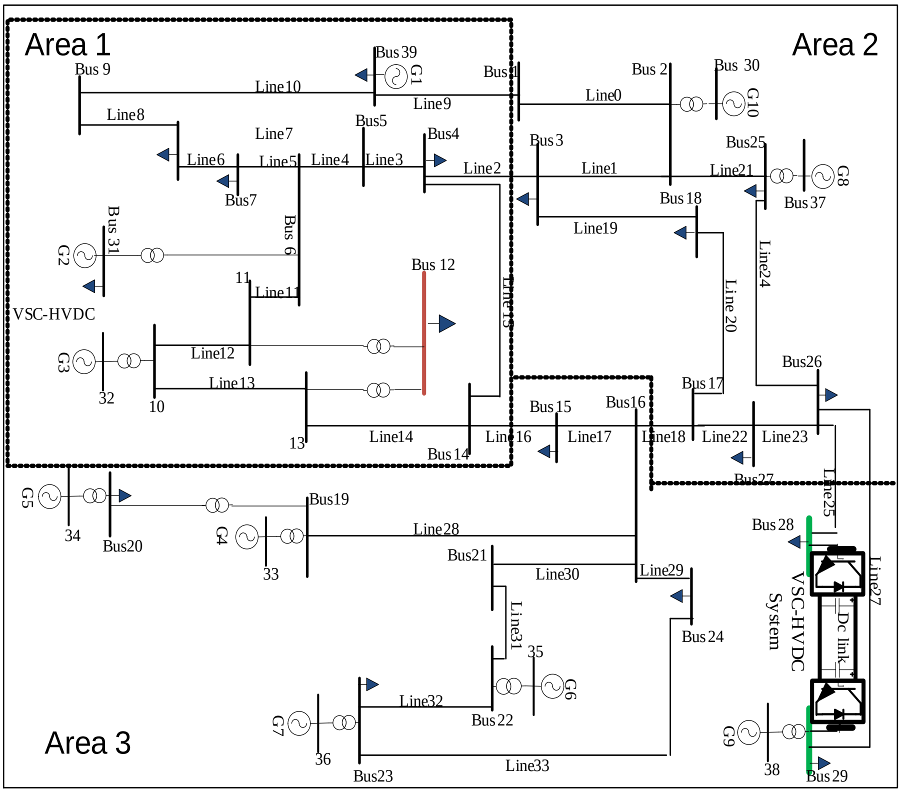

Figure 7. IEEE 39 bus test system with VSC-HVDC

- **The Control Mode-2:** In this control strategy, the first converter works at fixed reactive power [Q-VDC] mode while the second convertor works at fixed active power [VAC-P] mode. It is calculated by the power flow of original system; the active and reactive power transferred between bus 28 and 29 are 350MW and -40 MVar respectively as the bus voltage of 29 is 1.0499 p.u. So, the first converter which works in [Q-VDC] mode is adjusted to [-40MVar, -1.0p.u] as the second converter which works in [VAC-P] mode is adjusted to [1.0499p.u -350MW]. In bus 28, when active power 1694.99MW and reactive power 227.07 MVAR, power flow is not convergence and the system is in maximum loading state. In this loading point voltages of the bus 12 and the bus 27 are 0.8p.u. and 0.8447p.u. respectively. In during simulation, inverter side converter bus connected the reactive power of synchronous generator has increased than 23.7MVar to 231.4MVar. The active power loss of AC system is 359.01MW. In the original AC system, active and reactive loads have been increased and loading margin obtained for Bus 28. In bus 28, when active power 1654.885MW and reactive power 221.702 MVAR, power flow is not convergence and the system is in maximum loading state. In this loading point voltages of the buses 28, 12, 27 and the bus 29 are 0.73p.u., 0.843p.u., 0.812 and 0.855p.u. respectively. During simulation, the reactive power of synchronous generator connected to bus 29 has increased from 22.84MVar to 1271.96MVar. In Figure 8, for all case studies P-V curves of buses 28, 12, 27 and 29 are shown together to compare. It can be seen by Figure 8a that the voltage stability for base status of the system is improved for bus 28 for both control modes. P-V curves of the most critical bus are drawn in Figure 8b and it can be concluded that the first control mode gives the best result for this bus. The P-V curves of buses 27 and 29 are given by Figures 8c and 8d, respectively. By inspecting the P-V curves of buses 27 and 29, it can be said that the first control mode gives best solution for voltage stability improvement for the system aforementioned above. The P-V curves given in Figures 8a-8d show that the [V_{AC}-V_{DC}] control strategy improves the system parameters better compared to [Q-V_{DC}] control strategy in perspective of voltage stability.

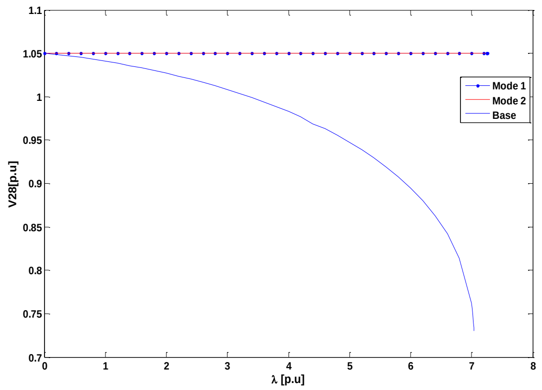

Figure 8a. P-V curve of bus 28 for both cases

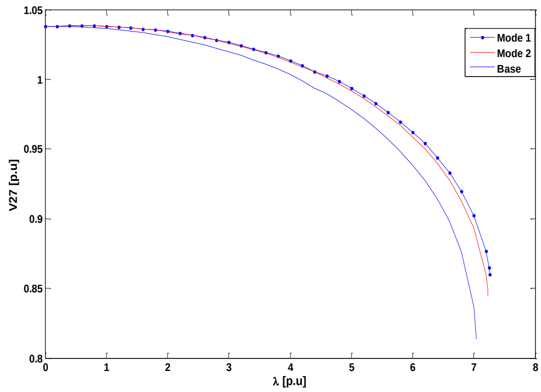

Figure 8b. P-V curve of bus 27 for both cases

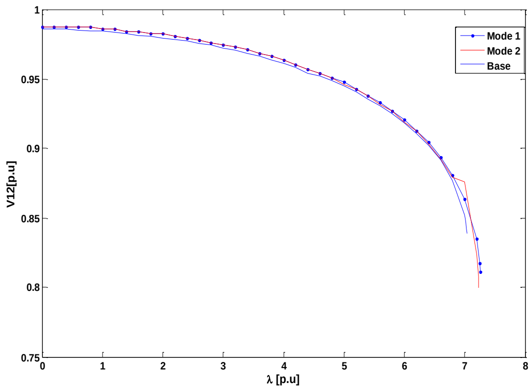

Figure 8c. P-V curve of bus 12 for both cases

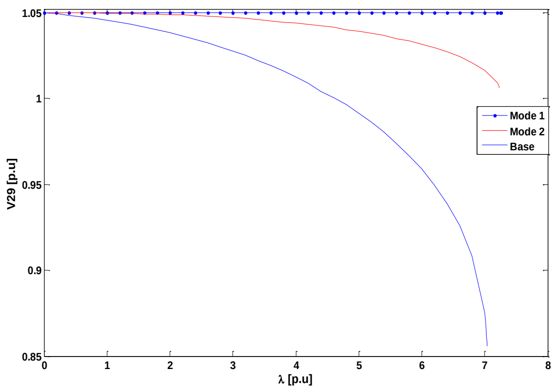

Figure 8d. P-V curve of bus 29 for both cases

6. CONCLUSIONS

In this paper, effect to voltage stability of VSC-HVDC control modes is investigated for AC system. In 39 bus test system, the power transfer has been done in two different control modes through VSC-HVDC to critical bus that is determined by sensitivity analysis and determined the best suitable control mode for voltage stability improvement. The simulation results indicate that the constant AC voltage control of VSC converter is superior to reactive power control in voltage stability and show that VSC-HVDC significantly improved the stability of the system compared to a pure AC line. To achieve a better enhancement of voltage stability, through VSC-HVDC variable power transfer should be preferred instead of constant power transfer. At last, the results of case studies compared with the original AC system are demonstrated by P-V curves and tables.

NOTICE

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