Nonlinear Control Design of VSC-MTDC Systems based on Backstepping Approach

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Abstract: This paper deals with the nonlinear control approach of Voltage Source Converter (VSC) based on MTDC (multi-terminal direct current) transmission systems. A nonlinear control approach based on Backstepping method is proposed for two different control methods: active power and DC voltage. The proposed control approach, based on Lyapunov theory, is capable of analytically obtaining a control laws in order to regulate the active power and dc bus voltage in an MTDC system. Furthermore, the dynamic interactions between the active power nonlinear control design and the DC voltage droop control are examined. Finally, the validity of the proposed control design approach is verified by time-domain simulations under the Matlab/ Simulink environment.

1 INTRODUCTION

The development of the renewable energy requires a reliable technology for transmission power over long distances. Since of the disadvantage of the High Voltage Alterning Current (HVAC) and with the progression of the power electronics, the High Voltage Direct Current (HVDC) technology is improved in (Setréus and Bertling, 2008). The high power self-commutated VSC, based on the Gate-Turn-Off (GTO) and Insulated Gate Bipolar Transistor (IGBT) using the Pulse Width Modulation (PWM) techniques, are the principal components in the transmission system HVDC. To this end, they are used serve to providing high quality AC output voltage to the grid or even to a passive load, and facilitate the control of the strongly coupled nonlinear system (Jovic et al., 2003).

The VSC based multiterminal VSC-HVDC power transmission system (VSC-MTDC) is an ideal approach to connect more then two HVDC station by a DC grid (Jacobson, 2011). Recently, the new Modular Multilevel Converter (MMC) is attractive for HVDC applications thanks to its modular structure (Belhaouane et al., 2014).

Many research have been discussed the modeling and control of a VSC-MTDC transmission system (Chen et al., 2006). Traditionally, the conventional Proportional Integral PI controllers are used to control the VSC-HVDC converters. However, the dynamic performance of such control scheme is poor, because of the strong interactions among the control loops (Rashed et al., 2008). The strong nonlinearity present in the system dynamics requires the use of nonlinear control techniques. Thus, a large number of controller for HVDC transmission systems based on different control techniques have been proposed to enhance the transient systems and dynamic stability. Several nonlinear control techniques are used to overcome difficulties during abnormal operating conditions especially under parametric uncertainties, faults and non-linear disturbances (Ramadan et al., 2012).

Further, the application of advanced nonlinear controls that is: robust control (Ramadan et al., 2008), (Moharana and Dash, 2010), optimal control (Sachdev et al., 1973), adaptive control (Reeve and Sultan, 1994), and controls-based on artificial intelligence (AI) (Dash et al., 1999), (Moharana et al., 2006), have been developed for improving transient stability of power systems (Colbia-Vega et al., 2008). These approaches are used to elaborate complex nonlinear controllers, characterized by a lack of complete knowledge of the dynamic characteristics of the system.

Recently, the Backstepping control design tech-

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niques have received an important attention because of its systematic and recursive design methodology for nonlinear feedback control (Jammazi, 2008), (Kim and Kim, 2003). In (Ruan et al., 2007), an adaptive Backstepping control method is proposed and uncertainties of AC grid current is considered. (Wang et al., 2013) proposed a Backstepping control design to ensure the stability of VSC-HVDC system in case of a parameter variations and external disturbances. To control an MTDC system, a feedback linearization strategy and Backstepping-like procedure are proposed in (Chen et al., 2013).

In this manuscript, an integral Backstepping control scheme is presented and applied on a multi-terminals VSC-HVDC transmission systems in order to regulate the reactive power, active power and the DC voltage where an integral action is added to ensure zero steady -state tracking error.

This paper is structured as follows. The mathematic model of VSC-MTDC station is given in 2. Based on Lyapunov theory, an integral Backstepping controller for each control mode is depicted in 3. Section 4 presents the simulation results by using Matlab/Simulink environment. At last, Conclusions are drawn in Section 5.

2 MODELING OF VSC-MTDC SYSTEM

In Fig. (1), the topology of Multi-terminal VSC-MTDC for interconnexion between n AC networks is depicted. It consists of DC cables with different length, identical voltage source converters (VSCs), and AC grids.

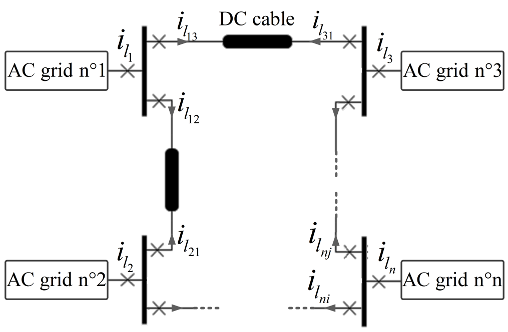

Figure 1: The interconnection between n terminals.

The configurations of the VSCs converter stations are identical. In Fig. 2, one VSC terminal is shown. L_s and R_s denote the inductance and the equivalent resistance of the converter inductor respectively. $\vec{i}_s$, $\vec{u}_m$ and $\vec{u}_g$ represent respectively the three phase AC current and the voltages of the both side of the reactor phase. The control of an MTDC transmission systems consist to control the VSCs converter either by DC bus voltage droop control mode "Us-Control" or AC power control mode "Pac-Control". The Pac-Control mode aim to control the active and reactive powers. The Us-Control mode allows to maintain the balance between power production and demand.

2.1 Average Model: Pac-Control Mode

The basic structure of the three phase VSC converter is depicted in Fig. 2. In Pac-Control mode, The DC voltage is considered fix. Applying Kirchhoff's voltage and current laws, it easy to obtain.

$$L_s \frac{d\vec{i}_s}{dt} + R_s \vec{i}_s = -\vec{u}_m + \vec{u}_g \tag{1}$$

Multiplying each term of the equation (1) by the Park matrix P_k, it follows that:

$$P_k \frac{d\vec{i}_s}{dt} = -\frac{R_s}{L_s} P_k \vec{i}_s - \frac{1}{L_s} P_k \vec{u}_m + \frac{1}{L_s} P_k \vec{u}_g \tag{2}$$

where P_k is the park transformation.
According to (2), the mathematical model of a VSC-HVDC station operating on Pac-Control mode is written as follows:

$$\begin{aligned} \frac{di_{sd}}{dt} &= -\frac{R_s}{L_s} i_{sd} + \omega i_{sq} - \frac{1}{L_s} u_{md} + \frac{1}{L_s} u_{gd} \\ \frac{di_{sq}}{dt} &= -\omega i_{sd} - \frac{R_s}{L_s} i_{sq} - \frac{1}{L_s} u_{mq} + \frac{1}{L_s} u_{gq} \end{aligned} \tag{3}$$

where i_{sd}, i_{sq} are the dq components of the VSC output current, u_{md}, u_{mq} and u_{gd}, u_{gq} are the dq components of the VSC output voltage, AC network voltage respectively.

2.2 Average Model: Us-Control Mode

In the "Pac-Control mode" presented above, the DC voltage is considered as constant voltage variable and presented by a fixed voltage DC source. Referring to Fig. 2 with the DC circuit "Us-Control", the DC source is replaced now by the capacitor equivalent C_s and current source.

By assuming a dq frame orientation such that $u_{gq} = 0$ pu and neglecting the power losses on both sides of the VSC converter, we get (Thomas et al., 2001) :

$$P_{AC} = P_{DC} \implies u_s i_m = \frac{3}{2}\left(u_{gd} i_{sd} + u_{gq} i_{sq}\right) \tag{4}$$

where i_m is the DC output current.
Using Eq. (3)-(4), we can obtain the following average model of the VSC-HVDC station operating on

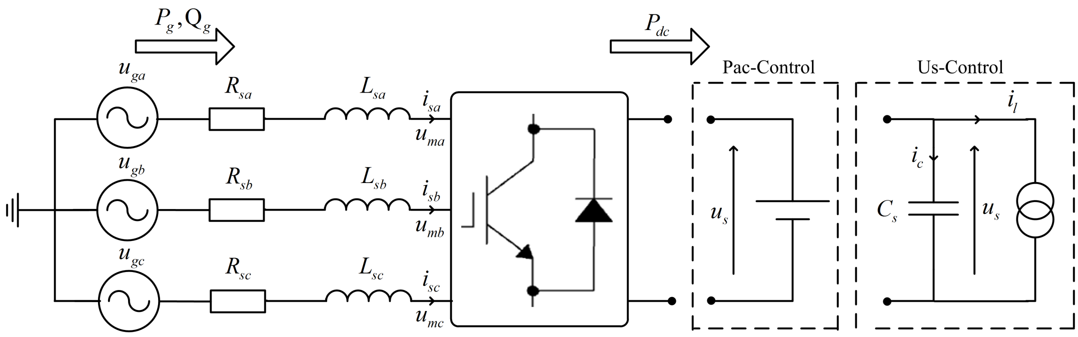

Figure 2: Basic structure of VSC converter.

Us-Control mode:

$$\begin{cases} \frac{di_{sd}}{dt} = -\frac{R_s}{L_s} i_{sd} + \omega i_{sq} - \frac{1}{L_s} u_{md} + \frac{1}{L_s} u_{gd} \\ \frac{di_{sq}}{dt} = -\omega i_{sd} - \frac{R_s}{L_s} i_{sq} - \frac{1}{L_s} u_{mq} \\ \frac{du_s}{dt} = \frac{3u_{gd}}{2C_s} \frac{i_{sd}}{u_s} - \frac{1}{C_s} \frac{P_l}{u_s} \end{cases} \tag{5}$$

2.3 DC Cable Model

The model of the DC transmission line connected to the DC side of ith and jth stations, is an equivalent circuit of T-type. L_{sr}, R_{sr} and C_{sr} denote respectively the equivalent inductance, resistance and capacitance of the cables. Then, the model of the DC cables is described as:

$$\begin{cases} \frac{di_{l_{ij}}}{dt} = -\frac{R_{sr}}{L_{sr}} i_{l_{ij}} - \frac{1}{L_{sr}} u_{l_{ij}} + \frac{1}{L_{sr}} u_{s_i} \\ \frac{di_{l_{ji}}}{dt} = -\frac{R_{sr}}{L_{sr}} l_{ji} - \frac{1}{L_{sr}} u_{l_{ij}} + \frac{1}{L_{sr}} u_{s_j} \\ \frac{du_{l_{ij}}}{dt} = \frac{1}{C_{sr}} \left(i_{l_{ij}} + i_{l_{ji}} \right) \end{cases} \tag{6}$$

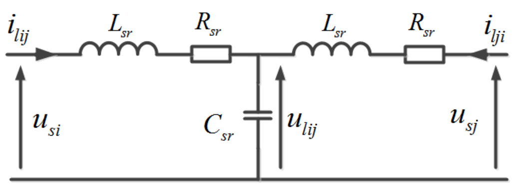

Figure 3: Simplified structure of DC cable (Thomas et al., 2001).

3 INTEGRAL BACKSTEPPING CONTROL SCHEME FOR VSC-MTDC SYSTEMS

In this section, we propose a backstepping control strategy including an integral action to ensure zero steady-state tracking error. The proposed backstepping controller is designed to keep the non-linearities useful to enhance the performance and robustness of control, unlike linearization methods. The determination of the control laws resulting from this approach is based on Candidate Lyapunov Functions (CLF) (Khalil, 2002), (Skjetne and Fossen, 2004).

The control purpose of an MTDC System is to regulate the DC voltage and to keep the power flow at its reference value. The first VSC terminal controlling both active and reactive powers, and all other terminals are endowed with voltage droop controller (Dierckxsens et al., 2012).

3.1 Integral Backstepping Controller of Pac-control Mode

This control mode aims to regulate the active and reactive powers. Considering the currents errors z_{isd} and z_{isq} defined by:

$$\begin{aligned} z_{isd} &= I_{sd}^{ref} - i_{sd} \\ z_{isq} &= I_{sq}^{ref} - i_{sq} \end{aligned} \tag{7}$$

Differentiating z_{isd} and z_{isq} with respect to time gives:

$$\begin{aligned} \dot{z}_{isd} &= \dot{I}_{sd}^{ref} + \frac{R_s}{L_s} i_{sd} - \omega i_{sq} + \frac{1}{L_s} u_{md} - \frac{1}{L_s} u_{gd} \\ \dot{z}_{isq} &= \dot{I}_{sq}^{ref} + \omega i_{sd} + \frac{R_s}{L_s} i_{sq} + \frac{1}{L_s} u_{mq} \end{aligned} . \tag{8}$$

where $\dot{I}_{sd}^{ref}$ and $\dot{I}_{sq}^{ref}$ are the time derivative of I_{sd}^{ref} and I_{sq}^{ref}, respectively.

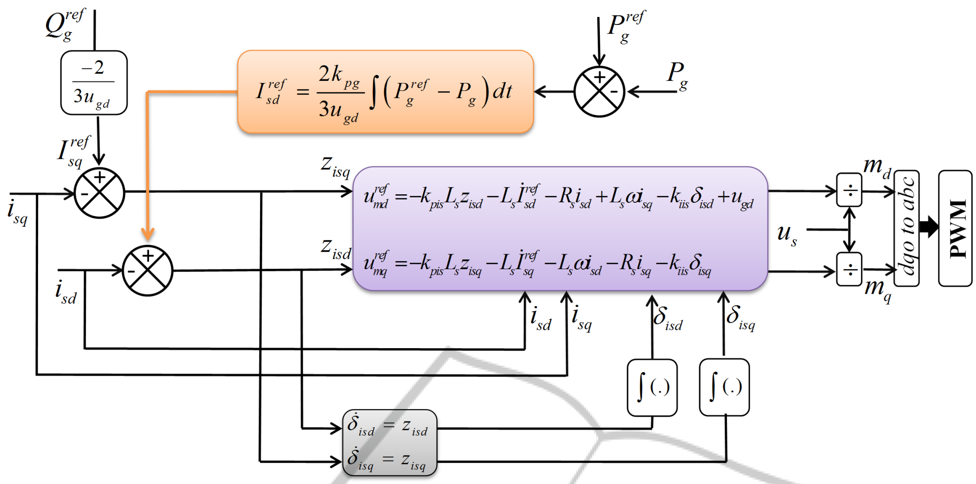

Figure 4: Block diagram of Backstepping method with integral action for P_{ac}-Control Mode.

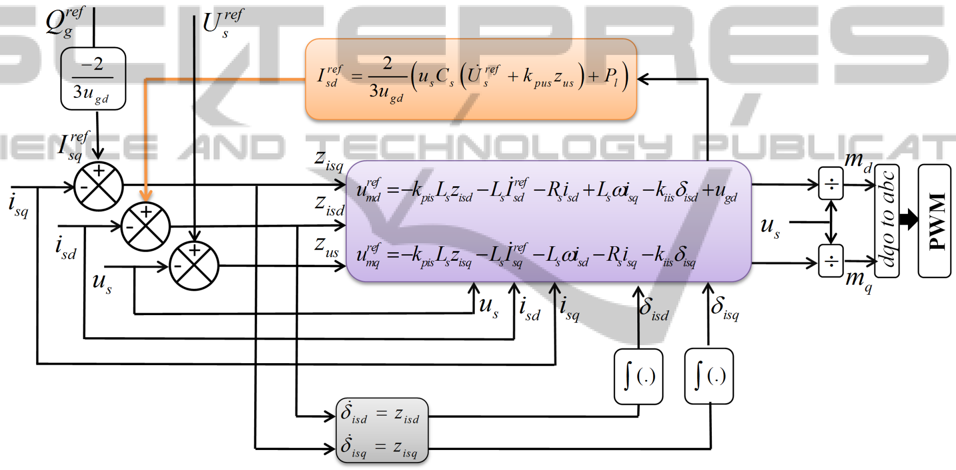

Figure 5: Block diagram of Backstepping method with integral action for U_s-Control Mode.

To investigate the stability of the errors model (7), a Lyapunov function V_{PQ} is chosen as:

$$V_{PQ} = \frac{1}{2}L_s z_{isd}^2 + \frac{1}{2}k_{iis}\,\delta_{isd}^2 + \frac{1}{2}L_s z_{isq}^2 + \frac{1}{2}k_{iis}\,\delta_{isq}^2 \quad (9)$$

where δ_{isd} and δ_{isq} are respectively the integral terms of z_{isd} and z_{isq}, $k_{iis} > 0$. The terms $\frac{1}{2}L_s z_{isd}^2$ and $\frac{1}{2}L_s z_{isq}^2$ represent the energy fluctuation of the AC reactance.

The derivative of V_{PQ} along the trajectories of (7) is given by:

$$\begin{aligned}\dot{V}_{PQ} = {} & z_{isd}\left(L_s \dot{I}_{sd}^{ref} + R_s i_{sd} - L_s \omega i_{sq} + u_{md} - u_{gd}\right) \\ & + z_{isq}\left(L_s \dot{I}_{sq}^{ref} + L_s \omega i_{sd} + R_s i_{sq} + u_{mq}\right) \\ & + k_{iis}\,\delta_{isd} z_{isd} + k_{iis}\,\delta_{isq} z_{isq}\end{aligned} \quad (10)$$

which leads to the following control laws:

$$\begin{aligned}u_{md}^{ref} &= -k_{pis}L_s z_{isd} - L_s \dot{I}_{sd}^{ref} - R_s i_{sd} + L_s \omega i_{sq} \\ &\quad - k_{iis}\delta_{isd} + u_{gd} \\ u_{mq}^{ref} &= -k_{pis}L_s z_{isq} - L_s \dot{I}_{sq}^{ref} - L_s \omega i_{sd} - R_s i_{sq} - k_{iis}\delta_{isq}\end{aligned} \quad (11)$$

yields:

$$\dot{V}_{PQ} = -k_{pis}L_s\left(z_{isd}^2 + z_{isq}^2\right) < 0 \quad (12)$$

where $k_{pis} > 0$.

The active and reactive powers are controlled through the currents i_{sd} and i_{sq} respectively, such as:

$$\begin{aligned}I_{sd}^{ref} &= \frac{2k_{pg}}{3u_{gd}}\int_0^t \left(P_g^{ref} - P_g\right)dt \\ I_{sq}^{ref} &= -\frac{2}{3u_{gd}}Q_g^{ref}\end{aligned} \quad (13)$$

The Backstepping control structure is deciped by Fig. 4.

3.2 Integral Backstepping Controller of Us-droop Control Mode

In this section, a droop voltage controller is designed to stabilize the DC voltage, decoupling the dq grid current and regulate the reactive power.
We consider the mathematical model given in (5). Firstly, we introduce $z_{us} = U_s^{ref} - u_s$, $z_{isd} = I_{sd}^{ref} - i_{sd}$, $z_{isq} = I_{sq}^{ref} - i_{sq}$, $\dot{\delta}_{isd} = z_{isd}$ and $\dot{\delta}_{isq} = z_{isq}$.

The time derivative of z_{us} is given as:

$$\dot{z}_{us} = \dot{U}_s^{ref} - \frac{3u_{gd}}{2C_s}\frac{I_{sd}^{ref}}{u_s} + \frac{1}{C_s}\frac{P_l}{u_s} \tag{14}$$

Let consider the following definite positive Lyapunov function:

$$V_{us} = \frac{1}{2}C_s z_{us}^2 \tag{15}$$

such that $\frac{1}{2}C_s z_{us}^2$ represents the energy fluctuation in the dc capacitor.
From the equation (5), the derivative of V_{us} along the trajectories of the system is given by:

$$\dot{V}_{us} = C_s z_{us}\left(\dot{U}_s^{ref} - \frac{3u_{gd}}{2C_s}\frac{I_{sd}^{ref}}{u_s} + \frac{1}{C_s}\frac{P_l}{u_s}\right) \tag{16}$$

Then, if $z_{isd} = 0$ and following the backstepping method in order to ensure stability of the tracking voltage, the virtual control law I_{sd}^{ref} is given by the following equation:

$$I_{sd}^{ref} = \frac{2}{3u_{gd}}\left(u_s C_s \dot{U}_s^{ref} + C_s k_{pus} u_s z_{us} + P_l\right) \tag{17}$$

Based on the above analysis, we get $\dot{V}_{us}$ as negative semidefinite function expressed as:

$$\dot{V}_{us} = -k_{pus} C_s z_{us}^2 < 0 \ , \ k_{pus} > 0 \tag{18}$$

After the conception of the virtual controller, the second step is to ensure the asymptotic stability of the global system via the direct Lyapunov method based on the new CLF. Then, differentiating the currents errors z_{isd} and z_{isq} with respect to time yields:

$$\begin{aligned} \dot{z}_{isd} &= \dot{I}_{sd}^{ref} + \frac{R_s}{L_s}i_{sd} - \omega i_{sq} + \frac{1}{L_s}u_{md} - \frac{1}{L_s}u_{gd} \\ \dot{z}_{isq} &= \dot{I}_{sq}^{ref} + \omega i_{sd} + \frac{R_s}{L_s}i_{sq} + \frac{1}{L_s}u_{mq} \end{aligned} \ . \tag{19}$$

where $\dot{I}_{sd}^{ref}$ and $\dot{I}_{sq}^{ref}$ are the time derivative of I_{sd}^{ref} and I_{sq}^{ref}, respectively.
The candidate Lyupanov Function chosen for the asymptotic stability of the global system is expressed as:

$$V_{PQ} = V_{us} + \frac{1}{2}L_s z_{isd}^2 + \frac{1}{2}k_{iis}\delta_{isd}^2 + \frac{1}{2}L_s z_{isq}^2 + \frac{1}{2}k_{iis}\delta_{isq}^2 \tag{20}$$

where $k_{iis} > 0$.
The derivative of V_{PQ} is given by:

$$\begin{aligned} \dot{V}_{PQ} = {} & z_{isd}\left(L_s \dot{I}_{sd}^{ref} + R_s i_{sd} - L_s \omega i_{sq} + u_{md} - u_{gd}\right) \\ & + z_{isq}\left(L_s \dot{I}_{sq}^{ref} + L_s \omega i_{sd} + R_s i_{sq} + u_{mq}\right) \\ & + k_{iis}\delta_{isd} z_{isd} + k_{iis}\delta_{isq} z_{isq} - k_{pus} C_s z_{us}^2 \end{aligned} \tag{21}$$

Similarly, by choosing the control laws as:

$$\begin{aligned} u_{md}^{ref} = {} & -k_{pis} L_s z_{isd} - L_s \dot{I}_{sd}^{ref} - R_s i_{sd} + L_s \omega i_{sq} \\ & - k_{iis}\delta_{isd} + u_{gd} \\ u_{mq}^{ref} = {} & -k_{pis} L_s z_{isq} - L_s \dot{I}_{sq}^{ref} - L_s \omega i_{sd} - R_s i_{sq} - k_{iis}\delta_{isq} \end{aligned} \tag{22}$$

$\dot{V}_{PQ}$, expressed by (23), is negative semidefinite.

$$\dot{V}_{PQ} = -k_{pus} C_s z_{us}^2 - k_{pis} L_s z_{isd}^2 - k_{pis} L_s z_{isq}^2 < 0 \tag{23}$$

where $k_{pis} > 0$.

Fig. 5 shows the structure of the control system derived from the second step of the Backstepping technique.

4 VALIDATION OF THE PROPOSED NONLINEAR CONTROL METHOD

To prove the effectiveness of the proposed control strategy, a simulation study was carried out under Matlab/Simulink environment. The test system is depicted in Fig. 6. It's composed on two onshore and offshore stations. It is worth pointing that each VSC converter is rated at 1000 MVA, 320 kVrms phase to phase AC voltage and a DC voltage of ± 320 kV.

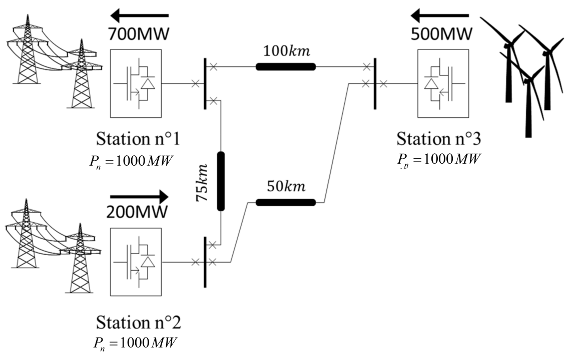

Figure 6: A three-terminal VSC-HVDC transmission system (Rault, 2014).

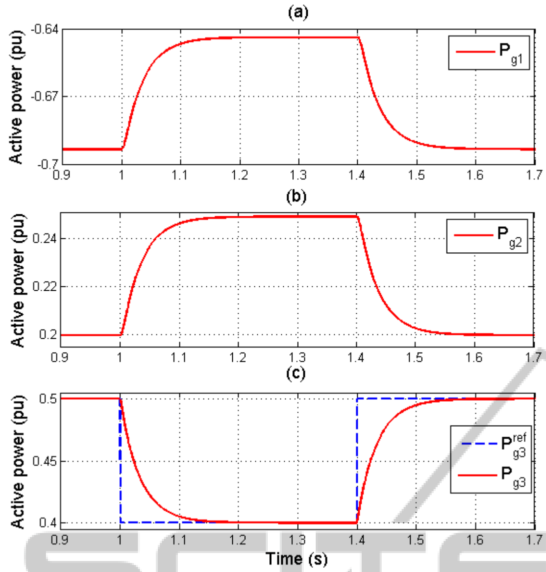

Figure 7: Behaviors of the active powers in the station n° 1, n° 2 and n° 3.

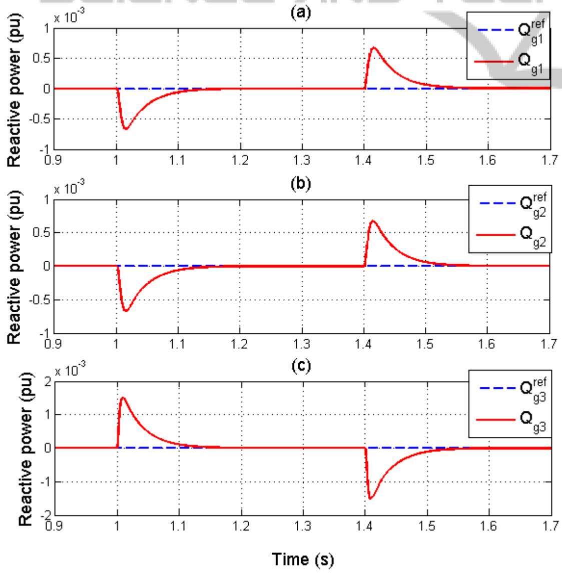

Figure 8: Behaviors of the reactive powers in the station n° 1, n° 2 and n° 3.

The major contribution is based on the control design devoted to endow the station n°1 and station n°2 with the Us-droop control as well as controlling the power flow via the station n°3.

The control gains ($k_{pus} = 500$, $k_{pg} = 30$, $k_{pis} = 10^3$ and $k_{iis} = 119.36$) are synthesised in order to ensure a response time for the grid currents around 10 ms, a response time for the active power equal to 100 ms and to define the droop value K to adjust the power deviation portion which is following through a converter station:

$$K\left(KV/MW\right) = \frac{\Delta u_s}{\Delta P_g} = \frac{1}{C_s k_{pus}} \qquad (24)$$

where:

- K is the droop value;
- ΔP_g is deviation of power injected into the AC grid;
- Δu_s is deviation of DC voltage.

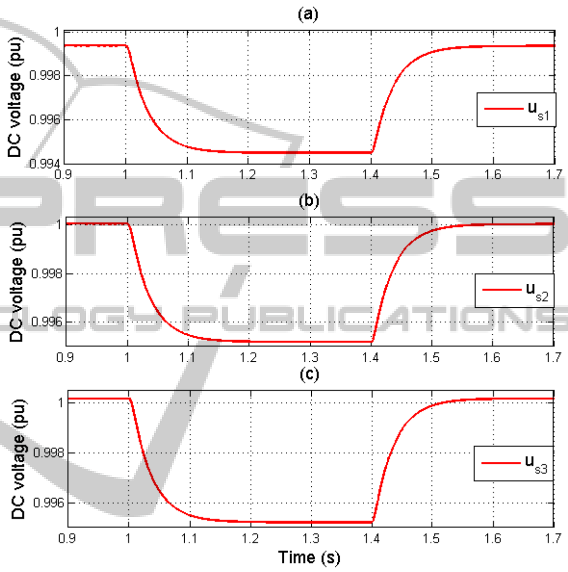

Figure 9: DC voltage behavior in the stations n° 1, n° 2 and n° 3.

Figs. (7)-(9) illustrate the behaviors of active power and DC bus voltage for each stations. At instant $t < 1$ s, the power delivered by the wind farm is 0.5 pu (500 MW). The power injected through the station n°2 to the DC grid is 0.2 pu (200 MW) and the power flow from DC grid to AC grid through station n°1 is 0.7 pu (700 MW). For instants t between 1 s and 1.1 s, the produced power by wind farm is decreased to 0.4 pu (400 MW). This loss of production is equally shared between the two onshore converter stations when they have the same droop value:

$$P_{g1} = -700 + \frac{100}{2} = -650\,MW$$

$$P_{g2} = 200 + \frac{100}{2} = 250\,MW$$

As shown in Fig. 9, this event leads to decrease the DC voltage level since there is less power transfer with regard to the previous operating point.

Simulations results (not shown here) show that the direct and quadrature current are decoupled. From Fig. 8, the reactive powers of each station is always track the reference signal $Q_{gi}^{ref} = 0$ pu (i=1,2,3).

5 CONCLUSION

In this paper, the Backstepping control technique based on direct Lyapunov method is extrapolated to the VSC-MTDC application. The controller is able to provide asymptotic stability for the power transmission system with multiple terminals. The control law is based on a Backstepping-like procedure which the stability of the whole transmission system is proved under the proposed controller. Simulations results show that the proposed control strategy is able to regulate the DC-bus voltage and the power flow with good dynamic performances.

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