An improved adaptive weighting function method for State Estimation in Power Systems with VSC-MTDC

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Abstract. This paper presents an effective approach for state estimation in power systems that include multi-terminal voltage source converter based high voltage direct current (VSC-MTDC), called improved adaptive weighting function method. The proposed approach is simplified in which the VSC-MTDC system is solved followed by the AC system. Because the new state estimation method only changes the weight and keeps the matrix dimension unchanged. Accurate and fast convergence of AC/DC system can be realized by adaptive weight function method. This method also provides the technical support for the simulation analysis and accurate regulation of AC/DC system. Both the theoretical analysis and numerical tests verify practicability, validity and convergence of new method.

1. Introduction
Voltage source converter, as a new transmission technology to support flexible DC power transmission, has drawn much more attentions in electric power system. It is now considered to be a feasible solution for connecting offshore wind farms due to its significant advantages over both current source converter (CSC) HVDC and traditional AC system [1] and the first project which is 400 MW, ±150kV two terminal VSC HVDC system for wind farms connection has been commissioned in Germany in 2010 [2]. The concept of “European Offshore Super grid” [3] has been proposed to build a VSC based subsea meshed DC grid which is used to connect the renewable offshore wind farms to the AC networks. Apart from line commutated converter (LCC), the VSC technology makes the extension to multi-terminal HVDC connections relatively easy. Quite a few papers have been published on VSC-MTDC steady state modeling for load flow [4, 5].

State estimation plays important role in Energy Management System (EMS). With rapid development of HVDC technologies, development of practical methods for AC/DC hybrid power system state estimation is an emergent demand. However, most papers have been published on AC systems, and only a few studies have so far been carried out on AC/DC systems state estimation which includes a generalized VSC MTDC model. In [6, 7], the state estimation was proposed for the two-terminal VSC-HVDC system and the MTDC system was not considered. Glover and Sheikoleslami [8] emphasized on the DC network state estimation without including the AC/DC interconnection system. Leita da Silva et al. [9] separated an AC/MTDC interconnected system into three subsystems, namely AC system, AC/DC interface and DC system. Jagatheesan and Duraiswamy [10] extended the fast decoupled state estimation technique originally applied on the AC system to the AC/DC system and proposed a sequential solution scheme to solve P-Q-DC iteratively. The sequential method is simple and can be easily appended to existing AC fast decoupled state estimators (FDSE). Zhang
boming [11] presents a new state estimation algorithm, called improved sequential method, which is based on the polar formulation.

Since VSC-MTDC has significant advantages in power systems and state estimation plays an important role in EMS, this paper presents a new state estimation algorithm, called improved adaptive weighting function method. This method decouples the AC system and the DC system by mathematic method according to the information matrices formed by the alternating solution method. And the residual error information of AC/DC system interface is fully utilized to realize accurate and fast convergence of AC/DC system by adaptive weight function. Tests on IEEE14 test system have been done and the results verify that this proposed method is efficient and valid.

2. WLS and FDSE state estimation algorithm

In recent years, with the expansion of the scale of power system and the development of power market, the reliability and accuracy of on-line safety and stability analysis, automatic generation control (AGC) and automatic voltage control (AVC) are becoming higher and higher. Real-time analysis and control of data sources, state estimation has become an indispensable part of the smart grid dispatch control system. Usually assume that the network parameters and wiring status is accurate to each node voltage amplitude and phase angle for the state estimation vector $X$, to obtain the measured value $Z$, for the measurement error $v$, the measurement equation can be written as:

$$z = h(x) + v$$

(1)

For a given set of measurement vectors, the estimator is obtained using weighted least square (WLS) criteria by minimizing the objective function:

$$J(x) = [z - h(x)]R^{-1}[z - h(x)]$$

(2)

The iterative correction formula of the basic weighted least squares method for minimizing the state estimation is obtained.

$$\Delta \hat{x}^k = [H^T(\hat{x}^k)R^{-1}H(\hat{x}^k)]^{-1}H^T(\hat{x}^k)R^{-1}[z - h(\hat{x}^k)]$$

(3)

$$\hat{x}^{k+1} = \hat{x}^k + \Delta \hat{x}^k = \hat{x}^k + [H^T(\hat{x}^k)R^{-1}H(\hat{x}^k)]^{-1}H^T(\hat{x}^k)R^{-1}[z - h(\hat{x}^k)]$$

(4)

According to the above iterative correction, until convergence, this time close to the minimum value of the objective function.

Since the basic weighted least squares estimation method needs a large amount of memory and a long computation time, a fast decoupled state estimation (FDSE) method is usually adopted. This is a well-recognized model of utility performance on high voltage networks. The quantity measurement, the state quantity and the measurement equation are decomposed into active and reactive power, and the hypothesis is introduced in the Jacobian matrix $H$:

$$\begin{align*}
\frac{\partial h_a}{\partial V} &\approx 0 \\
\frac{\partial h_r}{\partial \theta} &\approx 0
\end{align*}$$

(5)

The modified equation of the state estimation of the fast decoupled method can be obtained:

$$\begin{align*}
A\Delta \theta^{(i)} &= a^{(i)} \\
B\Delta V^{(i)} &= b^{(i)}
\end{align*}$$

(6)

Where $A$ is the symmetry matrix of active constants, $B$ is the symmetrical matrix of reactive power, $a$ is the active free vector, and $b$ is the reactive free vector.
The state estimation algorithm is only applicable to the AC system. When the MTDC system is included in the power system, the system state cannot be completely described by the voltage and phase angle calculated by the AC state estimation. After the flexible DC system is put into operation, there may be measurement quality problems. The original state estimation model does not consider the flexible DC system model, the lack of straight state system state estimation function cannot be achieved straight system and AC system mixed state estimation calculation, is not suitable for flexible DC transmission system, it is necessary to the original state estimation Methods to supplement, expansion and innovation.

3. VSC-MTDC Model

The steady-state model of the VSC-MTDC is shown as follows:

\[
A = V_0^4 \left[ (-B_a) \right]^T R_{a}^{-1} \left[ -B_a \right] \\
B = V_0^2 \left[ (-B_r) \right]^T R_{r}^{-1} \left[ -B_r \right] \\
a^{(i)} = V_0^2 \left[ (-B_a) \right]^T R_{a}^{-1} \left( z_a - h_a \right) V^{(i)}, \theta^{(i)} \\
b^{(i)} = V_0^2 \left[ (-B_r) \right]^T R_{r}^{-1} \left( z_r - h_r \right) V^{(i)}, \theta^{(i)}
\]  

(7)

The relationship between the converter input voltage and DC voltage is:

The relationship between the converter input voltage \( U_{ci} \) and DC voltage is:
\[
U_{ci} = \mu_d M_i U_{di} / \sqrt{2}
\] (10)

Where: \( \delta_i = \delta_{ai} - \delta_{ci} \), \( M_i \) is the modulation degree, \( \mu_d \) is the DC voltage utilization.

As the impedance of the converter bridge forward, so the active power \( P_{ci} \) into the converter bridge is equal to the active power output \( P_{di} \), \( Q_{ci} \) is the reactive power into the converter bridge, \( I_{di} \) is the DC current.

\[
P_{di} = U_{di} I_{di}
\] (11)

\[
P_{ci} = U_{ci} / X_{hi} \sin \delta_i
\] (12)

\[
Q_{ci} = -U_{ci} / X_{hi} (U_{ci} - U_{ai} \cos \delta_i)
\] (13)

DC system network equation is as follows:

\[
I_{di} = U_{ai} G
\] (14)

Where: \( G \) is network conductance.

3. Proposed method for state estimation

3.1. Dimension invariant function

The state estimation of flexible DC transmission usually adopts the WLS method. There are a total of 11 variables appeared: \( U_{di}, U_{ci}, U_{ai}, M_i, \delta_i, I_{di}, P_{ai}, Q_{ai}, P_{ci}, Q_{ci}, P_{di} \). The power flow equations of all the AC nodes in the VSC-MTDC system can be expressed as follows:

\[
\Delta P_{ai} = P_{ai} - P_{ai}(U_{ai}, \delta_{ai})
\] (15)

\[
\Delta Q_{ai} = Q_{ai} - Q_{ai}(U_{ai}, \delta_{ai})
\] (16)

The power flow equations of all the DC nodes in the VSC-MTDC system can be expressed as follows:

\[
\Delta P_i = P_i - \sum f_{Pai}(U_{act}, \delta_{act}, U_{ai}, \delta_i, U_{di}, \delta_{ci}, M) = 0
\] (17)

\[
\Delta Q_i = Q_i - \sum f_{Qai}(U_{act}, \delta_{act}, U_{ai}, \delta_i, U_{di}, \delta_{ci}, M) = 0
\] (18)

In addition to the above pseudo-measurement equations, the actual measurement equations in DC system and AC/DC interface system are shown as follows:

\[
\Delta d_1 = \Delta P_{si} = P_{si} - f_{Pai}(U_{ai}, \delta_i, U_{di}, \delta_{ci}, M) = 0
\] (19)

\[
\Delta d_2 = \Delta Q_{si} = Q_{si} - f_{Qai}(U_{ai}, \delta_i, U_{di}, \delta_{ci}, M) = 0
\] (20)

\[
\Delta d_3 = \Delta P_{di} = U_{di} I_{di} - f_{Pci}(U_{ai}, \delta_i, U_{di}, \delta_{ci}, M) = 0
\] (21)

\[
\Delta d_4 = \Delta I_{di} = I_{di} - U_{di} G = 0
\] (22)
\[ \Delta d_5 = U_{n_i}^m - U_{n_i}^i = 0 \]  \hspace{1cm} (23)
\[ \Delta d_6 = U_{d_i}^m - U_{d_i}^i = 0 \]  \hspace{1cm} (24)
\[ \Delta d_7 = \delta_{i}^m - \delta_{i}^i = 0 \]  \hspace{1cm} (25)
\[ \Delta d_8 = M_{i}^m - M_{i}^i = 0 \]  \hspace{1cm} (26)
\[ \Delta d_9 = I_{d_i}^m - I_{d_i}^i = 0 \]  \hspace{1cm} (27)

Where \( U_{n_i}^m \) is measurement value, \( U_{n_i}^i \) is true value.

The VSC HVDC converter can control its active and reactive power injection independently in the system.

1) \( U_{dc}, Q \) control: The DC bus voltage keeps constant through adjusting the active power injection of the converter. The reactive power is scheduled to a set point and the \( U_{dc}, Q \) control constraint is

\[ 0 = U_{d_i} - U_{d_i}^{ord} + \eta_1 \]
\[ 0 = Q_{si} - Q_{si}^{ord} + \eta_2 \]  \hspace{1cm} (28)

2) \( U_{dc}, U_{ac} \) control: The DC bus voltage and AC bus voltage keeps constant and the \( U_{dc}, U_{ac} \) control constraint is

\[ 0 = U_{d_i} - U_{d_i}^{ord} + \eta_3 \]
\[ 0 = U_{n_i} - U_{n_i}^{ord} + \eta_4 \]  \hspace{1cm} (29)

3) \( P, Q \) control: The active power and the reactive power is constant and the \( P, Q \) control constraint is

\[ 0 = P_{si} - P_{si}^{ord} + \eta_5 \]
\[ 0 = Q_{si} - Q_{si}^{ord} + \eta_6 \]  \hspace{1cm} (30)

4) \( P, U_{ac} \) control: The active power and AC bus voltage is constant and the \( P, U_{ac} \) control constraint is

\[ 0 = P_{si} - P_{si}^{ord} + \eta_7 \]
\[ 0 = U_{n_i} - U_{n_i}^{ord} + \eta_8 \]  \hspace{1cm} (31)

According to each control mode, there are two known quantities are determined, so the corresponding state of state estimation mathematical model also needs to be adjusted. The result shows that the Jacobian matrix and corresponding factor table under different control modes will change in dimension, and because of the switch of control mode, the state estimation mathematical model is changed due to the different states' adding and exiting.

In order to avoid the above-mentioned situation, the state estimation of the VSC-MTDC system needs the algorithm of high precision, high speed and low memory. Therefore, without changing the number of the state, give greater weight to the known state. According to the above-mentioned different control methods, in order to guarantee the fast convergence of the state estimation iterations, we give a large weight \( R_{max} \) to the known quantity measurement in the weighted least squares estimation.

The estimate of known quantities is obtained using WLS criteria by minimizing the objective function:

\[ J(x) = [\Delta z - H(x_0)\Delta x]^TR_{max}^{-1}[\Delta z - H(x_0)\Delta x] \]  \hspace{1cm} (32)
Where, the H dimension keeps constant. It is benefit for program development.

3.2. Adaptive weight function
According to equation (19-27), there are only three unknown variables between AC system and DC system by using sequential method. They are $P_n$, $Q_n$, $U_t$.

Control by a single inverter control is analyzed as follows:

1) $U_{dc}$, $Q$ control: AC and DC systems are iterated alternately. The difference $\Delta P_n$, $\Delta U_t$ between the AC and DC results of the two systems are the convergence signs of the state estimation of the VSC-MTDC system.

2) $U_{dc}$, $U_{ac}$ control: $\Delta P_n, \Delta Q$ are the convergence signs of the state estimation

3) $P_t, Q$ control: $\Delta U_t$ is the convergence sign of the state estimation

4) $P_t, U_{ac}$ control: $\Delta Q$ is the convergence sign of the state estimation

In order to improve accuracy and fast convergence of AC/DC system, adaptive weight function method is proposed. Because most of the known measured values are accurate in the actual power system, they are given a bigger weight than the state quantity $x_0^{(0)}$ measured in the first state estimation calculation. For the AC system iterative calculation and the DC system iteration calculation, after the convergence of the two independently, the state quantity $x_{ac}$ calculated from the AC system and the state quantity $x_{dc}$ calculated from the DC system are obtained.

The absolute value of the difference between the two and the initial state measurement value is calculated:

$$
\Delta c_{nd} = |x_{ac} - x_{dc}|
$$

$$
\Delta c_{t0} = |x_{dc} - x_0^{(0)}|
$$

$$
\Delta c_{ba} = |x_0^{(0)} - x_{ac}|
$$

The above three differences from small to large $\Delta c_1 < \Delta c_2 < \Delta c_3$, and set the adaptive comparison threshold $\Delta c_{\varepsilon}$ compared, there will be the following four cases:

$$
\Delta c_{\varepsilon} < \Delta c_1 < \Delta c_2 < \Delta c_3
$$

1

$$
\Delta c_1 < \Delta c_{\varepsilon} < \Delta c_2 < \Delta c_3
$$

2

$$
\Delta c_1 < \Delta c_2 < \Delta c_{\varepsilon} < \Delta c_3
$$

3

$$
\Delta c_1 < \Delta c_2 < \Delta c_3 < \Delta c_{\varepsilon}
$$

4

The next state $x_0^{(l+1)}$ after calculating is different in each case:

$$
x_0^{(l+1)} = \begin{cases} 
   \frac{x_{ac} + x_{dc} + x_0^{(l)}}{3} & (1), (3), (4) \\
   \frac{x_{c1}^1 + x_{c2}^2}{2} & (2) 
\end{cases}
$$

Where $x_{c1}^1$, $x_{c2}^2$ is related with $\Delta c_1$, $x_0^{(l+1)}$ is measurement during the next iteration, $l \geq 0$, $x_0^{(0)}$ is initial measurement.
Next, put this average measurement $x_{0}^{(j+1)}$ into iterative calculation in AC system and DC system separately. And add bigger weight to this average measurement $x_{0}^{(j+1)}$:

$$J(x) = [\Delta z - H(x_{0}^{(j+1)})\Delta x]^T R_{max}^{-1} [\Delta z - H(x_{0}^{(j+1)})\Delta x]$$ (36)

Keep iterative calculate until satisfied the equation:

$$\Delta c_{1} < \Delta c_{2} < \Delta c_{3} < \varepsilon$$ (37)

Where $\varepsilon$ is the VSC-MTDC system initial measurement.

Compared with traditional state estimation, it can only be applied to AC system, and it cannot provide good data for VSC-MTDC system. The sequential state estimation calculation method of the AC and DC system considering the VSC-MTDC can solve the integrated state estimation and calculation problem of the AC system and the multi-terminal flexible DC transmission system hybrid system, and is used for realizing the VSC-MTDC AC and DC system Mixed state estimation calculation, to provide real-time accurate AC-DC system operating status. The method of calculating Jacobian matrix state - of - the - art state estimation based on variable weight is proposed, and the mathematic model of DC system is simplified. AC / DC system is proposed to solve AC / DC system alternately, and the residual error information of AC / DC system interface is fully utilized to realize accurate and fast convergence of AC / DC system by adaptive weight function. And the calculated result provides the technical support for the simulation analysis and accurate regulation of AC / DC system.

4. Case Study

In order to test the approach proposed in this paper, IEEE 14 bus system is used for simulation. Figure 2 is the modified IEEE14 node AC-DC hybrid system, where VSC1, VSC2 and VSC3 are assumed to operate at the node 2, 5, 4 orderly. Improved adaptive weighting function method and sequential method are applied to solve the system. All the Equivalent reactance is set to XL= 0.15, R = 0.006 and the resistance of DC circuit is Rd= 0.03, VSC1 is in $U_{dc}$, Q control mode ($U_{d1}$, ref = 2.0000, $Q_{s1}$, ref = 0.2099), VSC2 is in P, Q control mode ($P_{s2}$, ref = -0.3601, $Q_{s2}$, ref = 0.0187); VSC3 is in P, Q control mode ($P_{s3}$, ref = -0.8663, $Q_{s3}$, ref = -0.0864).

![Figure 2. Modified IEEE -14 -bus AC -DC system](image_url)
Table 1. State estimation results of AC system.

| Node No. | \( U_{qi} \) | \( \delta_{qi} \) | \( U_{si} \) | \( \delta_{si} \) |
|----------|--------------|----------------|--------------|----------------|
| 1        | 1.0600       | 0.000          | 1.0600       | 0.000          |
| 2        | 1.0288       | -6.048         | 1.0289       | -6.049         |
| 3        | 1.0116       | -15.129        | 1.0120       | -15.129        |
| 4        | 1.0406       | -14.129        | 1.0406       | -14.122        |
| 5        | 1.0113       | -4.033         | 1.0113       | -4.034         |
| 6        | 1.0702       | -12.159        | 1.0702       | -12.159        |
| 7        | 1.0669       | -15.704        | 1.0666       | -15.696        |
| 8        | 1.0923       | -15.699        | 1.0919       | -15.691        |
| 9        | 1.0543       | -16.546        | 1.0541       | -16.539        |
| 10       | 1.0479       | -16.043        | 1.0476       | -16.037        |
| 11       | 1.0538       | -14.242        | 1.0538       | -14.240        |
| 12       | 1.0555       | -13.259        | 1.0556       | -13.262        |
| 13       | 1.0490       | -13.596        | 1.0491       | -13.597        |
| 14       | 1.0324       | -16.241        | 1.0323       | -16.236        |

Table 2. State estimation results of DC system.

| DC node No. | method | \( P_i (MW) \) | \( Q_i (MVAr) \) | \( \delta (°) \) | \( M \) | \( U_d \) | \( I_d \) |
|-------------|--------|----------------|----------------|----------------|------|---------|---------|
| VSC1        | Improved | 124.6501       | 20.9900        | 10.3324        | 0.8220 | 2.0000  | 0.6197  |
| VSC1        | Sequential | 124.6502      | 20.9900        | 10.3233        | 0.8220 | 2.0000  | 0.6197  |
| VSC2        | Improved | -36.0099       | 1.8700         | -3.0340        | 0.8293 | 1.9919  | -0.1805 |
| VSC2        | Sequential | -36.0100     | 1.8700         | -3.0340        | 0.8293 | 1.9920  | -0.1808 |
| VSC3        | Improved | -86.6303       | -8.6400        | -6.7075        | 0.8743 | 1.9893  | -0.4392 |
| VSC3        | Sequential | -86.6300    | -8.6400        | -6.7073        | 0.8743 | 1.9893  | -0.4389 |

Table 1 and Table 2 show the state estimation results of AC/DC system by using different state estimators. Apparently the results of two algorithms are very similar and an inspection of the results indicates that the improved adaptive weighting function method can converge to acceptable state with the required tolerance. And from Table 2, it can be seen that the VSC1 and VSC2 and VSC3 output voltage phase angles are lagging behind the AC bus voltage phase angle of the corresponding node, so that VSC1 absorbs the active power from the AC grid, VSC2, VSC3 to the AC power grid into the active power.

Table 3. Comparison of performances between improved and sequential algorithms

| Method | No. of iterations | Improved method | Sequential method |
|--------|------------------|----------------|------------------|
|        |                  | 5              | 11               |
| Iteration time/s | 0.07285 | 0.1186         |

From table 3, it is noted that the sequential estimator needed more iterations than the improved estimator. It’s because in the derivation procedure of the improved method we have assumed Jacobian matrix unchanged in (32). It is also observed that less iterations and less solution time for the improved adaptive weighting function method as compared to the sequential method is because the weights of the same state quantities in different systems are considered.

5. Conclusion
This paper presents a novel and efficient approach which called improved adaptive weighting function method is suitable for the state estimation in the VSC-MTDC system. The new state estimation
method keeps the matrix dimension unchanged through changing the weight and the progress of incorporation adaptive weight function into the state estimation has been described in detail. Moreover, it is easy to realize the proposed method through extending an existing AC sequential method. Simulation results in modified IEEE 14 bus system demonstrate the effectiveness of the proposed state estimation algorithm.

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References
[1] ABB Group, It’s time to connect – Technical description of HVDC Light technology, [Online].
[2] ABB Grid connection of offshore wind farms – BorWin1, [Online].
[3] D. Van Hertem and M. Ghandhari, “Multi-terminal VSC HVDC for the European Supergrid: Obstacles,” Renew. Sustain. Energy Rev., vol. 14, no. 9, pp. 3256-3163, Dec. 2010.
[4] J. Beerten, S. Cole, and R. Belmans, "Generalized Steady-State VSCMTDC Model for Sequential AC/DC Power Flow Algorithms," IEEE Trans. Power Syst., vol. 27, no. 2, pp. 821-829, May 2012.
[5] Xiao-Ping Zhang, "Multiterminal Voltage-Sourced Converter-Based HVDC Models for Power Flow Analysis," IEEE Trans. Power Syst., vol. 19, no. 4, pp. 1877-1884, Nov. 2004.
[6] Antonio de la Villa Jaén, Eonrique Acha and Antonio Gómez Expósito,"Voltage Source Converter Modeling for Power System State Estimation: STATCOM and VSC-HVDC," IEEE Trans. Power Syst., vol. 23, no. 4, pp. 1552-1559, Nov., 2008.
[7] Guoqiang Sun, Yuyan Li, Zhitong Wei and Fang Ye, “State estimation of power system with VSC-HVDC,” Electric Power Automation Equipment, vol. 30, No. 9, pp. 6-12, Sep., 2010.
[8] J. D. Glover and M. Sheikoleslami, “State estimation of interconnected HVDC/AC systems,” IEEE Trans. Power Apparatus and Systems, vol. 102, pp. 1805-1810, June 1983.
[9] A. M. Leita da Silva, R. B. Prada, and D. M. Falcao, “State estimation for integrated multi-terminal DC/AC systems,” IEEE Trans. Power Apparatus and Systems, vol. 104, pp. 2349-2355, Sept. 1985.
[10] R. Jegatheesan and K. Duraiswamy, “AC/multi-terminal DC power system state estimation—A sequential approach,” Electric Machines and Power Systems, vol. 12, pp. 27-42, 1987.
[11] Qifeng Ding, T. S. Chung and Boming Zhang, "An improved sequential method for AC/MTDC power system state estimation," in IEEE Transactions on Power Systems, vol. 16, no. 3, pp. 506-512, Aug 2001.