

# A weight modification sequential method for VSC-MTDC power system state estimation

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**Abstract.** This paper presents an effective sequential approach based on weight modification for VSC-MTDC power system state estimation, called weight modification sequential method. The proposed approach simplifies the AC/DC system state estimation algorithm through modifying the weight of state quantity to keep the matrix dimension constant. The weight modification sequential method can also make the VSC-MTDC system state estimation calculation results more accurate and increase the speed of calculation. The effectiveness of the proposed weight modification sequential method is demonstrated and validated in modified IEEE 14 bus system.

## 1. Introduction

As a result, the negative impact of the highly developed industry is not enough to prevent the adverse impact, leading to the global three major crises: shortage of resources, environmental pollution and ecological damage. Flexible DC transmission technology can effectively use new energy to help improve the ecological environment. To support flexible DC Power transmission, voltage source converter plays an important role in power systems. 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,  $\pm 150$  kV 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 has drawn more attentions in EMS, this paper presents a new state estimation algorithm, called weight modification sequential 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 rapid convergence of AC/DC system by weight modification. Results obtained on IEEE14 test systems have been presented.

## 2. AC state estimation algorithm

Nowadays, state estimation has become an indispensable part of energy management system. The goal of the state estimator in the power system is to give the best estimate of the state of the power system to minimize the effect of the measurement error. The mathematical model of state estimation can be expressed as:

$$z = h(x) + v \quad (1)$$

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 weighted least square (WLS) state estimation is designed to find the system state  $x$  by solving the following optimization problem:

$$J(x) = [z - h(x)]^T R^{-1} [z - h(x)] \quad (2)$$

The solution of the nonlinear equation (2) can be obtained by an iterative procedure as shown below:

$$\Delta \hat{x}^k = [H^T(\hat{x}^k) R^{-1} H(\hat{x}^k)]^{-1} H^T(\hat{x}^k) R^{-1} [z - h(\hat{x}^k)] \quad (3)$$

$$\hat{x}^{k+1} = \hat{x}^k + \Delta \hat{x}^k = \hat{x}^k + [H^T(\hat{x}^k) R^{-1} H(\hat{x}^k)]^{-1} H^T(\hat{x}^k) R^{-1} [z - h(\hat{x}^k)] \quad (4)$$

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  $H$ :

$$\frac{\partial h_a}{\partial V} \approx 0 \quad \frac{\partial h_r}{\partial \theta} \approx 0 \quad (5)$$

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

$$\begin{aligned} A\Delta\theta^{(l)} &= a^{(l)} \\ B\Delta V^{(l)} &= b^{(l)} \end{aligned} \quad (6)$$

Where A-the symmetry matrix of active constants

B-the symmetrical matrix of reactive power

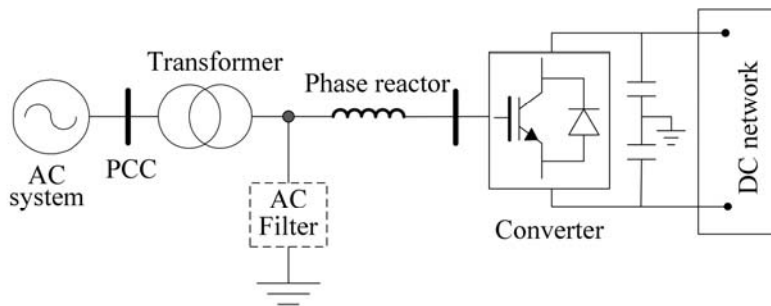
a-the active free vector, b-the reactive free vector.

The above state estimation approach is only suit for the AC system. When the MTDC system is added to the AC power system, the system state cannot be calculated by the WLS state estimation.

### 3. DC state estimation algorithm

#### 3.1. VSC-MTDC Model

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



**Figure 1.** Schematic diagram of VSC –MTDC.

From figure 1, where  $\dot{U}_{ci} = U_{ci} \angle \delta_{ci}$  is the converter input voltage.  $\dot{U}_{ti} = U_{ti} \angle \delta_{ti}$  is from the AC side the node voltage which is connected to inverter.  $R_i + X_{li}$  is the equivalent impedance for the rheological and commutation bridges.  $P_{si} + Q_{si}$  is the inverter input power.

Since  $R_i \ll X_{li}$ , the converter input power is:

$$P_{si} = \frac{U_{ti} U_{ci}}{X_{li}} \sin \delta_i \quad (7)$$

$$Q_{si} = \frac{U_{ti}}{X_{li}} (U_{ti} - U_{ci} \cos \delta_i) \quad (8)$$

The converter input voltage  $U_{ci}$  is:

$$U_{ci} = \mu_d M_i U_{di} / \sqrt{2} \quad (9)$$

Where:  $\delta_i = \delta_{si} - \delta_{ci}$ ,  $M_i$  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.

$$P_{di} = U_{di} I_{di} \quad (10)$$

$$P_{di} = P_{ci} = \frac{U_{ti} U_{ci}}{X_{li}} \sin \delta_i \quad (11)$$

$$Q_{ci} = \frac{-U_{ci}}{X_{li}} (U_{ci} - U_{ti} \cos \delta_i) \quad (12)$$

DC system network equation is:

$$I_{di} = U_{di} G \quad (13)$$

Where: G is network conductance.

### 3.2. VSC-MTDC measurement equations

The state estimation of flexible DC transmission usually adopts the WLS method. There are a total of 11 variables appeared:  $U_{di}, U_{ci}, U_{ti}, M_i, \delta_i, I_{di}, P_{si}, Q_{si}, P_{ci}, Q_{ci}, P_{di}$ .

The DC nodes' power flow equations in the VSC-MTDC system are:

$$\Delta P_{ti} = P_{ti} - \sum f_{P_{aci}}(U_{aci}, \delta_{aci}, U_{ti}, \delta_{ti}) - f_{P_{si}}(U_{ti}, \delta_{ti}, U_{di}, \delta_{ci}, M) = 0 \quad (14)$$

$$\Delta Q_{ti} = Q_{ti} - \sum f_{Q_{aci}}(U_{aci}, \delta_{aci}, U_{ti}, \delta_{ti}) - f_{Q_{si}}(U_{ti}, \delta_{ti}, U_{di}, \delta_{ci}, M) = 0 \quad (15)$$

The AC nodes' power flow equations in the VSC-MTDC system are:

$$\Delta P_{ai} = P_{ai} - P_{ai}(U_{ai}, \delta_{ai}) \quad (16)$$

$$\Delta Q_{ai} = Q_{ai} - Q_{ai}(U_{ai}, \delta_{ai}) \quad (17)$$

#### 4. AC/DC state estimation

The actual measurement equations in AC/DC system are shown as follows:

$$\Delta P_{si} = P_{si} - f_{Psi}(U_{ti}, \delta_{ti}, U_{di}, \delta_{ci}, M) = 0 \quad (18)$$

$$\Delta Q_{si} = Q_{si} - f_{Qsi}(U_{ti}, \delta_{ti}, U_{di}, \delta_{ci}, M) = 0 \quad (19)$$

$$\Delta P_{di} = U_{di} I_{di} - f_{Pci}(U_{ti}, \delta_{ti}, U_{di}, \delta_{ci}, M_i) = 0 \quad (20)$$

$$\Delta I_{di} = I_{di} - U_{di} G = 0 \quad (21)$$

$$U_{ti}^m - U_{ti}^t = 0 \quad (22)$$

$$U_{di}^m - U_{di}^t = 0 \quad (23)$$

$$\delta_i^m - \delta_i^t = 0 \quad (24)$$

$$M_i^m - M_i^t = 0 \quad (25)$$

$$I_{di}^m - I_{di}^t = 0 \quad (26)$$

Where  $U_{ti}^m$  is measurement value,  $U_{ti}^t$  is true value.

The VSC HVDC converter has four control modes when operating:

- 1)  $U_{dc}$ ,  $Q$  control: The DC bus voltage and the reactive power keep constant. The  $U_{dc}$ ,  $Q$  control constraint is

$$\begin{aligned} U_{di} - U_{di}^{ord} &= 0 \\ Q_{si} - Q_{si}^{ord} &= 0 \end{aligned} \quad (27)$$

- 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

$$\begin{aligned} U_{di} - U_{di}^{ord} &= 0 \\ U_{ti} - U_{ti}^{ord} &= 0 \end{aligned} \quad (28)$$

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

$$\begin{aligned} P_{si} - P_{si}^{ord} &= 0 \\ Q_{si} - Q_{si}^{ord} &= 0 \end{aligned} \quad (29)$$

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

$$\begin{aligned} P_{si} - P_{si}^{ord} &= 0 \\ U_{ti} - U_{ti}^{ord} &= 0 \end{aligned} \quad (30)$$

Since the different control mode has different constant state measurement. Under different control modes, the Jacobian matrix and corresponding factor table will change in dimension, and because of the switch of control mode, the number of Jacobian matrix dimension is changed through the different states' adding and exiting.

In this paper, in order to keep the dimension unchanged, we give a large weight  $R_{\max}$  to the known quantity measurement under different control modes in the weighted least squares estimation. Put large weight  $R_{\max}$  to the states as follows:

- 1)  $U_{dc}, Q$  control: Put large weight  $R_{\max}$  to  $U_{di}, Q_{si}$
- 2)  $U_{dc}, U_{ac}$  control: Put large weight  $R_{\max}$  to  $U_{di}, U_{ti}$
- 3)  $P, Q$  control: Put large weight  $R_{\max}$  to  $P_{si}, Q_{si}$
- 4)  $P, U_{ac}$  control: Put large weight  $R_{\max}$  to  $P_{si}, U_{ti}$

This approach achieves the goal of making the state estimation algorithm of high precision, high speed and low memory. The estimate of known state measurements is obtained using WLS by minimizing the objective function:

$$J(x) = [\Delta z - H(x_0)\Delta x]^T R_{\max}^{-1} [\Delta z - H(x_0)\Delta x] \quad (31)$$

Where, the  $H$  dimension is not changed.

By using sequential method, there are three unknown variables between AC system and DC system they are  $P_{si}, Q_{si}, U_t$ . The AC and DC decoupling calculations are implemented. Each iteration process involves AC iterations and DC iterations until they both converge independently and the AC/DC system convergence overall.

Under different control mode, the AC/DC system has different state estimation convergence sign. The convergence sign of the state estimation analyzed as follows:

1)  $U_{dc}, Q$  control:

The difference  $\Delta P_{si}, \Delta U_t$  are the convergence signs of the state estimation between results of the AC and DC systems.

2)  $U_{dc}, U_{ac}$  control:

$\Delta P_{si}, \Delta Q_{si}$  are the convergence signs of the state estimation

3)  $P, Q$  control:

$\Delta U_t$  is the convergence sign of the state estimation

4)  $P, U_{ac}$  control:

$\Delta Q_{si}$  is the convergence sign of the state estimation

A weight modification sequential method is proposed so as to improve accuracy and fast convergence of AC/DC system. The algorithm gives an initial weight  $R_{ac}^{(0)}$  to the unknown state quantity  $x_0^{(0)}$  from AC side and gives an initial weight  $R_{dc}^{(0)}$  to the unknown state quantity  $x_0^{(0)}$  from DC side in the first state estimation calculation. After the convergence of the AC system iterative calculation and the DC system iteration calculation, the state quantity  $x_{ac}$  is calculated by the AC system and the state quantity  $x_{dc}$  is calculated by the DC system.

The absolute value of the difference between the AC and DC systems is calculated:

$$\Delta c_{ad} = |x_{ac} - x_{dc}| \quad (32)$$

If the absolute value is more than the system adaptive comparison threshold  $\Delta c_\varepsilon$ :

$$\Delta c_\varepsilon < \Delta c_{ad} \quad (33)$$

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

$$x_0^{(l+1)} = \frac{R_{dc}x_0^{(0)} + R_{ac}x_0^{(0)}}{R_{dc} + R_{ac}} \quad (34)$$

Where  $x_0^{(l+1)}$  is measurement during the next iteration,  $l \geq 0$ ,  $x_0^{(0)}$  is initial measurement.

Next, put this average measurement  $x_0^{(l+1)}$  into iterative calculation in AC system and DC system separately. And add bigger weight  $R_{\max}$  to this average measurement  $x_0^{(l+1)}$ :

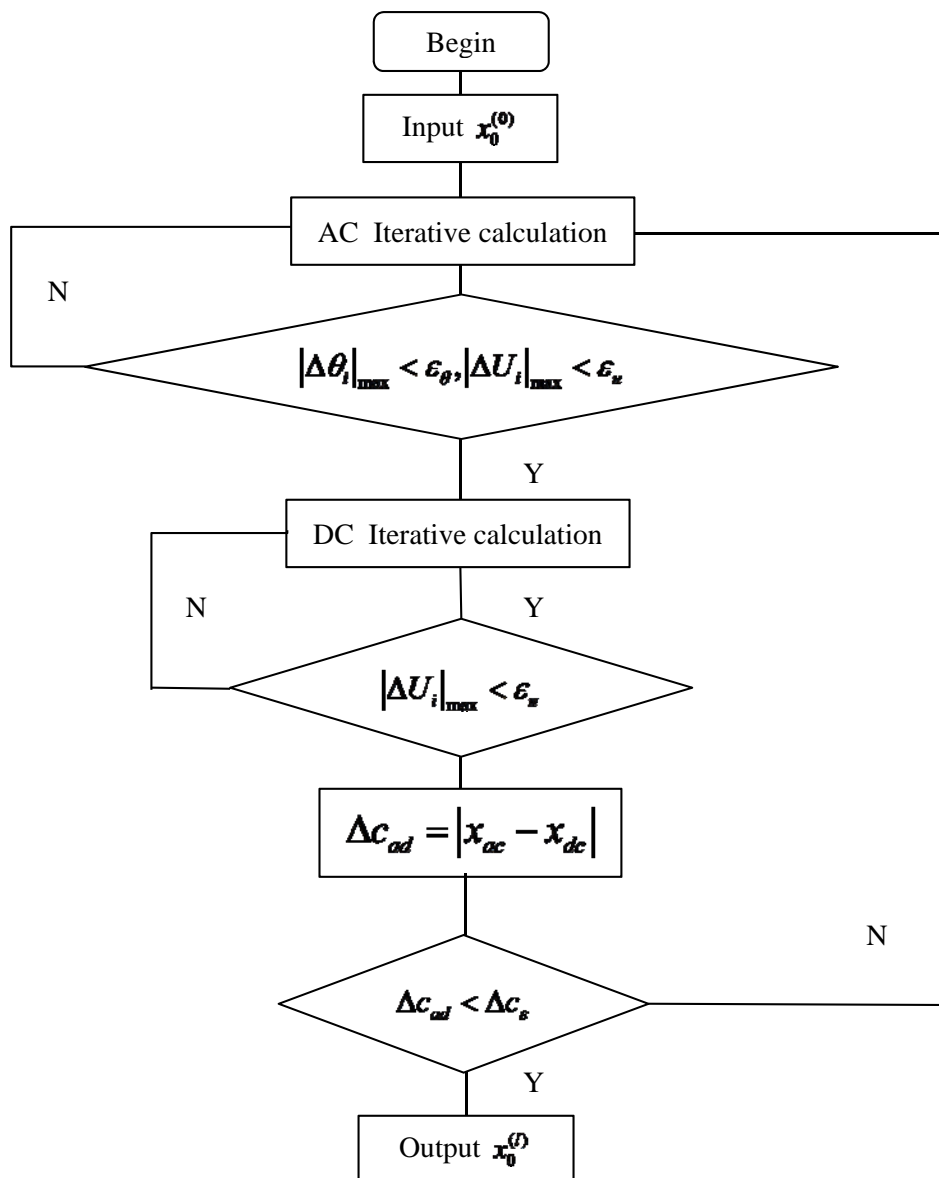
$$J(x) = [\Delta z - H(x_0^{(l+1)})\Delta x]^T (R_{ac} / R_{dc} + R_{\max})^{-1} [\Delta z - H(x_0^{(l+1)})\Delta x] \quad (35)$$

Keep iterative calculate until satisfied the equation:

$$\Delta c_{ad} < \Delta c_{\varepsilon} \quad (36)$$

Based on the effective method of weight modification, it provides a good data section for AC / DC power network, which provides technical support for power grid dispatching control. The modification of the weight of the AC / DC system can effectively accelerate the convergence of the state estimation. While minimizing the interference of undesirable data, the algorithm satisfies the AC / DC grid state estimation with VSC-MTDC.

The program flow chart is as follows:

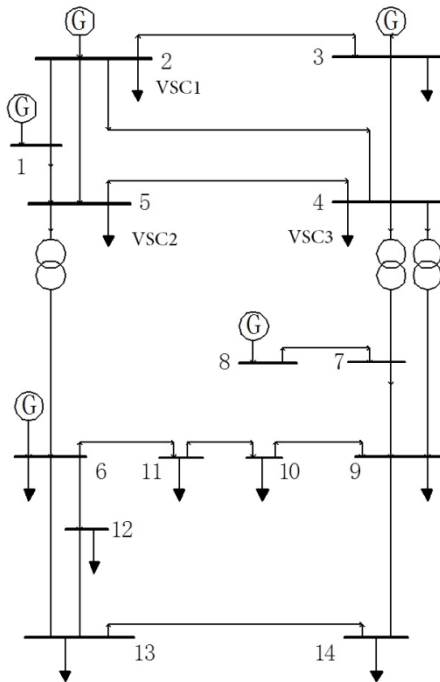


**Figure 2.** Program flow chart



### 5. Case Study

IEEE 14 bus system is used for simulation to test the approach proposed in this paper. Figure 3 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  $X_L = 0.15$ ,  $R = 0.006$  and the resistance of DC circuit is  $R_d = 0.03$ , 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 3.** Modified IEEE -14 -bus AC -DC system

**Table 1.** State estimation results of AC system.

Method	Proposed method		Sequential method	
Node No.	$U_{ii}$	$\delta_{ii}$	$U_{ii}$	$\delta_{ii}$
1	1.0600	0.000	1.0600	0.000
2	1.0289	-6.049	1.0289	-6.049
3	1.0119	-15.129	1.0120	-15.129
4	1.0406	-14.123	1.0406	-14.122
5	1.0113	-4.034	1.0113	-4.034
6	1.0702	-12.159	1.0702	-12.159
7	1.0666	-15.698	1.0666	-15.696
8	1.0920	-15.693	1.0919	-15.691
9	1.0541	-16.540	1.0541	-16.539
10	1.0477	-16.038	1.0476	-16.037
11	1.0538	-14.240	1.0538	-14.240
12	1.0556	-13.261	1.0556	-13.262
13	1.0491	-13.596	1.0491	-13.597
14	1.0323	-16.237	1.0323	-16.236

**Table 2.** State estimation results of DC system

DC node No.	method	$P_s(MW)$	$Q_s(MVAr)$	$\delta(^{\circ})$	$M$	$U_d$	$I_d$
VSC1	Proposed	124.6502	20.9900	10.3325	0.8220	2.0000	0.6195
	Sequential	124.6502	20.9900	10.3323	0.8220	2.0000	0.6197
VSC2	Proposed	-36.0099	1.8700	-3.0340	0.8293	1.9920	-0.1805
	Sequential	-36.0100	1.8700	-3.0340	0.8293	1.9920	-0.1808
VSC3	Proposed	-86.6303	-8.6400	-6.7073	0.8743	1.9893	-0.4389
	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. Obviously the results of two algorithms are very close.

**Table 3.** Comparison of performances between improved and sequential algorithms

Method	Improved method	Sequential method
No. of iterations	9	11
Iteration time/s	0.0908	0.1186

From table 3, it is noted that the sequential estimator needed more iterations than the weight modification sequential estimator. Because the weights of the same state quantities in different systems are modified.

## 6. Conclusion

This paper presents a weight modification sequential method which 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 of matrix. The weight modification sequential method has been described in detail above. It is only through extending an existing AC sequential method can realize the proposed method. Simulation results in modified IEEE 14 bus system demonstrate the effectiveness of the weight modification sequential method.

## Acknowledgments

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