# An improved model-free adaptive control algorithm for VSC-HVDC power transmission systems

## UN MEJORADO CONTROL ADAPTATIVO SIN MODELO, APLICADO A SISTEMAS DE TRANSPORTE DE ENERGÍA EN C.C. (VSC-HVDC)

DOI: http://dx.doi.org/10.6036/7741 | Recibido: 01/07/2015 • Aceptado: 31/08/2015

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## RESUMEN

- El incremento continuado de la demanda de electricidad ha hecho que la mejora en la eficiencia y en la operación de la red de transporte sea un aspecto esencial en la actualidad. Además, todavía existen muchas áreas remotas en el mundo que carecen de acceso a la electricidad. Los sistemas de transporte de alta tensión en corriente continua con convertidores por fuentes de tensión (Voltage-source converter based high voltage direct current -VSC-HVDC) pueden ayudar a satisfacer ambas demandas.
  En estos sistemas, el control de la potencia activa de la estación convertidora constituye un desafío. En este artículo se presenta un algoritmo de control adaptativo sin modelo mejorado (an improved model-free adaptive control -iMFAC) para solventar dicho problema. Considerando que el sistema VSC-HVDC es un sistema no lineal con estructura desconocida, el algoritmo realiza una linealización dinámica en tiempo real utilizando una estrategia dirigida por los datos para construir el modelo. Posteriormente, se deriva una ley de control del iMFAC, calculando una función objetivo. Además, los parámetros del iMFAC se auto ajustan en tiempo real utilizando únicamente los datos de entrada y salida medidos. El análisis matemático propuesto justifica la existencia de solución. Finalmente, la efectividad del algoritmo propuesto se valida sobre un sistema HVDC flexible con cinco terminales.
- **Palabras clave:** iMFAC, VSC-HVDC, regulación de la potencia activa, estación convertidora.

## 1. INTRODUCTION

With the rapid developments in the high-voltage high power fully controlled semiconductor, Voltage Source Converter based High Voltage Direct Current (VSC-HVDC) has being become more and more popular in the power transmission system. Due to the use of VSC-technology and pulse width modulation (PWM), the VSC-HVDC achieves many advantages, such as independent and rapid control of the active and reactive power, controllable short-circuit current contribution and reduction of the short circuit current [1]. The experience in offshore wind power system demonstrates that the VSC-HVDC is a competitive solution to achieve long-distance power transmission [2]. Comparing to the conventional HVDC transmission, the VSC-HVDC doesn't require commutating voltage from the connected AC grid. So it is effective in supplying power to isolated and remote loads. Due to its advantages, it is possible that VSC-HVDC will be one of the most important components of power transmission and distribution system in the future.

In the VSC-HVDC power transmission system, the management of the active power is a key issue. Because the active power control interacted with the inner converter current control and the outer voltage droop control, impacts on both AC and DC system [3]. The independent control of real and active power improves the power system stability and ensures an efficient power transfer. Using the linear matrix inequality (LMI) technology, Wang proposed a robust non-fragile controller to manipulate the rectifying side and inversion side of the flexible DC transmission system, respectively [4]. Zhang and Nee investigated a power-synchronization control in VSC-HVDC [5]. Zheng and Zhou utilized a pole assignment technology to design a damping controller and improve the active power in VSC-HVDC [6]. Moharana et al. combined the input-output linearization and sliding mode-control strategy, and present a robust nonlinear controller for VSC-HVDC power transmission [7].

Although the mentioned methods work well, they need to build the mathematical model of VSC-HVDC. It is difficult to get the model with high accuracy when the scale of VSC-HVDC system becomes larger and larger. As a result, the performance of above model-based control algorithm cannot meet the requirement of VSC-HVDC. Since the cost of data acquisition and storage has continuously decreased owing to advances in information technology, data-driven modelling and model-free control algorithms have gained popularity in the industrial processes, such as Proportional Integral Differentiation (PID) controller [8,9], model-free adaptive control

[10], iterative learning control [11,12], unfalsified control [13], virtual reference feedback tuning [14], and iterative feedback tuning [15], etc.

Among those algorithms, the PID controller is widely used in DC power transmission systems, for example, the d-q coordination control [16], direct current control [17], direct power control [18], and so on. However the performance of PID controller will be degenerated when it is used in complex and large-scale VSC-HVDC system (high nonlinearity, times variation). Furthermore, it is difficult to determine the optimal parameters of PID controller in the practical VSC-HVDC system. Although a genetic algorithm (GA) can get the suitable parameters under considering various operational cases of the VSC-HVDC system [19,20], the GA-based PID controller is very complex and its computational burden is high.

To successfully manipulate the active power (or DC voltage, frequency) of the converter station in the VSC-HVDC system, an improved model-free adaptive control (iMAFC) is proposed in this paper. The key idea of iMFAC is to construct an equivalently dynamical linearization time-varying model for the VSC-HVDC system at the operation points[21-23]. Then, the iMFAC scheme is derived using the optimal technology with the properties of error convergence and bounded-input and bounded-output (BIBO) stability. And the parameters of the iMAFC is tuned online by using the measured input/output data only. As a result, a robustness of iMFAC can be achieved to reject the exogenous disturbances.

The remainder of this paper is organized as follows. Section 2 describes the topological structure and traditional control diagram of the VSC-HVDC power transmission system. Section 3 gave the iMFAC designment using a dynamical linearization method, as well as, the convergence analysis of the proposed algorithm. Section 4 presented a real experiment to evaluate the performance of iMFAC. Conclusions are summarized in Section 5.

## 2. PROBLEM FORMULATION

### 2.1. THE TOPOLOGICAL STRUCTURE OF VSC-HVDC SYSTEM

A typical VSC-HVDC system includes two converter stations built with VSC topologies (shown in Fig. 1). One is a rectifier station, the other is an inverter station. The two VSC are connected either back-to-back or through a DC cable, depending on the application. The VSC topology is the conventional two-level three-phase converter. Reactors are the ties of power exchanges between VSC and AC system. The AC filters are used to absorb high frequency harmonics. Transformer T is to transform AC voltage into secondary voltage adapted to DC link in the converter.

As shown in Fig.1, the main function of VSC-HVDC is to transform the DC power from the rectifier to the inverter. The key part is the voltage source converter which is achieved by the IGBTs and Pulse-Width Modulation (PWM). IGBTs and PWM are combined together to constitute the valves which is used to create any desired voltage waveforms. Using different PWM pattern, it is possible to make any change in waveform, phase and magnitude instantaneously [24]. As a result, the VSC can be considered as a controllable voltage source and VSC-HVDC is regarded as a synchronous machine without mass that can control active and reactive power almost instantaneously.

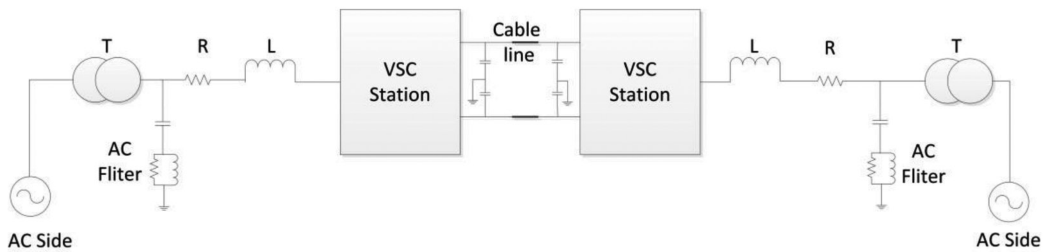



*Fig. 1: Topological structure of a VSC-HVDC system*

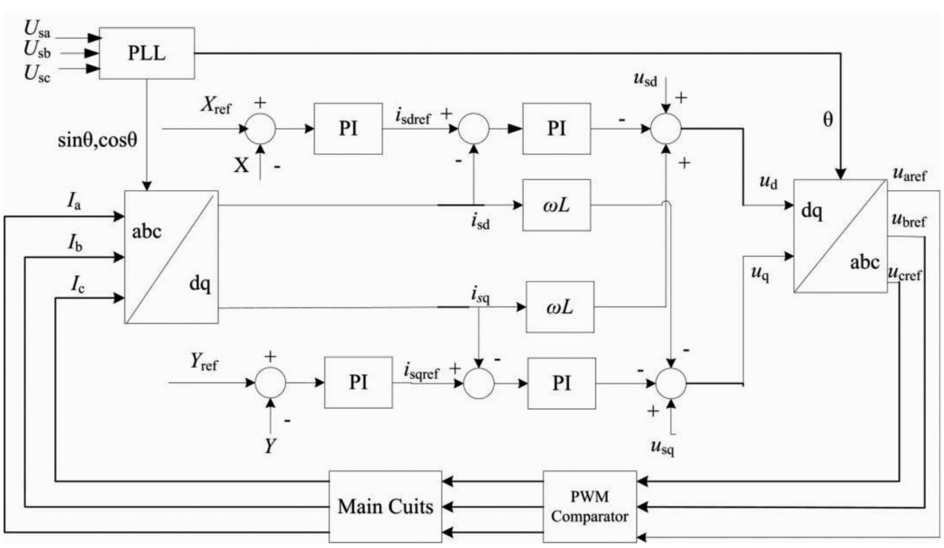



*Fig. 2: Controllers in the VSC-HVDC system*

### 2.2. CONTROLLERS IN VSC-HVDC SYSTEM

As mentioned before, the converter in VSC-HVDC system is typically controlled through PWM. Similarity to the traditional HVDC system, there are two PI controllers. One is to control the DC voltage, the other is to control the active power (shown in Fig. 2). The power flow in VSC-HVDC system is bidirectional in this system.

In Fig.2, Phase Locked Loop (PLL) is having a phase tracking mechanism where a synchronized output with input phase and frequency. This mechanism is used to synchronize current and AC side voltage to get a unity power factor operation. A 3-phase ($U_{sa}$, $U_{sb}$, $U_{sc}$) AC voltage input is given to PLL model. This model is implemented on d-q-frame by controlling $q$ axis voltage ie. $u_q$ to zero. PI controllers are used to achieve this purpose. Furthermore, the AC current is manipulated by the fast current controller of the inner loop and its reference ($i_{sdref}$, $i_{sqref}$) is given by the controller of the outer loop. The outer controllers consist either of AC voltage and reactive power controllers, and either of DC voltage or active power controllers. The reference value of the active current can be derived from the DC voltage controller, the active power controller and the frequency controller, the reference value of the reactive current can be obtained from the AC voltage controller, the reactive power controller. In all these controllers, integrators can be used to eliminate the steady state errors. Each of these controllers generates a reference value for the inner current controller. The inner controller is implemented in the d-q frame and achieves d-q decoupling control, which consists of a PI regulator, a current dependent decoupling factor, and a feed-forward controller of AC voltage. The control can be achieved by transforming voltage and current vectors from abc-to dq-frame.

In Fig.2, X denotes DC voltage, active power or frequency; Y is reactive power or AC voltage. Active current ($i_{sd}$) is used to control either of active power flow or DC voltage level. Similarly, the reactive current ($i_{sq}$) is used to control either of reactive power flow into stiff grid connection or AC voltage support in weak grid connection.

Using the a-b-c to d-q transformations, the converter 3-phase currents and voltages are expressed in 2-axis d-q reference frame, synchronously rotating at given AC frequency w.

$$\begin{vmatrix} u_d \\ u_q \end{vmatrix} = R\begin{vmatrix} i_{sd} \\ i_{sq} \end{vmatrix} + L\frac{d}{dt}\begin{vmatrix} i_{sd} \\ i_{sq} \end{vmatrix} + L\begin{vmatrix} 0 & -\omega \\ \omega & 0 \end{vmatrix}\begin{vmatrix} i_{sd} \\ i_{sq} \end{vmatrix} + \begin{vmatrix} u_{sd} \\ u_{sq} \end{vmatrix} \tag{1}$$

where $R$ and $L$ are the aggregated resistance and inductance between the converter and the grid respectively. $u_{sd}$ and $u_{sq}$ are the converter input voltages in d-q reference frame. $i_{sd}$ and $i_{sq}$ are the active and reactive currents.

The voltage equations in d-q synchronous reference frame are

$$\begin{cases} L\dfrac{di_{sd}}{dt} = -Ri_{sd} + \omega Li_{sq} - u_{sd} + u_d \\ L\dfrac{di_{sq}}{dt} = -Ri_{sq} - \omega Li_{sd} - u_{sq} + u_q \end{cases} \tag{2}$$

The power balance relationship between the AC input and DC output is given as follows,

$$p = \frac{3}{2}\left(u_{sd}i_{sd} + u_{sq}i_{sq}\right) \tag{3}$$

Inside the current control block, there are two PI regulators, respectively for d and q axis current control. They transform the error between the comparison of d and q components of current into voltage value. As seen from the figure 2 and Eq.(2), the VSC-HVDC is a multiple-input multiple output, strongly coupled system. And it is difficult to realize the exact decoupled control with general linear control strategies.

## 3. IMPROVED MFAC CONTROLLER

### 3.1. MODELLING BASED ON DATA-DRIVEN

As mentioned before, it is difficult to build the first principle model of the HVDC power transmission system. The reason is that the system is complex, multivariable, strongly coupled. In order to model the HVDC system using the data-driven strategy, the power $p(k)$ and the active current $i_{sd}(k)$ are set as $y(k)$ and $u(k)$ respectively. Then, the HVDC system can be expressed as a NARMAX form:

$$y(k+1) = f\left(y(k),\cdots,y(k-n_y),u(k),\cdots,u(k-n_u)\right) \tag{4}$$

where $y(k)\in R$, $u(k)\in R$ are system output and input at time instant $k$, respectively; $n_y$, $n_u$ are orders of system; $f(.)$ is unknown nonlinear function with continuous partial derivatives with respect to its arguments, which can be expressed in polynomial, rational, wavelet, or neural network forms.

The NARMAX model should be satisfied two assumptions as follows.

**A1.** The partial derivative of $f(.)$ is continuous and exits respecting to the $u(k)$.

**A2.** The system (4) is generalized Lipschitz stability, that is, $|\Delta y(k+1)| \leq b|\Delta u(k)|$ for any $k$ and $\Delta u(k)$, where $\Delta y(k+1)= y(k+1)-y(k)$, $\Delta u(k) = u(k)- u(k-1)$ and $b$ is a positive constant.

**Remark 1:** The two assumptions are reasonable and acceptable from a practical viewpoint. Assumption A1 is a typical condition of control system design for general nonlinear system. Assumption A2 poses a limitation on the rate of change of the system output. From the 'energy' point of view, the energy rate increasing inside a system cannot go to infinite if the energy rate of change of input is in a finite altitude. Clearly it is reasonable to the VSC-HVDC system.

**Theorem 1:** Given the nonlinear system (4) satisfying the assumptions A1 and A2, and $\Delta u(k) \neq 0$, there exists $\phi(k)$ which makes,

$$\Delta y(k+1) = \varphi(k)\Delta u(k) \tag{5}$$

where $|\phi(k)| \leq b$ is named as the pseudo-partial-derivative (PPD).

Proof. According to the Eq.(4), the $\Delta y(k+1)$can be formulated as

$$\begin{aligned}\Delta y(k+1) &= f\left(y(k), y(k-1),\cdots, y(k-n_y), u(k), u(k-1),\cdots, u(k-n_u)\right)\\ &- f\left(y(k-1), y(k-2),\cdots, y(k-n_y-1), u(k-1), u(k-2),\cdots, u(k-n_u-1)\right)\\ &= f\left(y(k), y(k-1),\cdots, y(k-n_y), u(k), u(k-1),\cdots, u(k-n_u)\right)\\ &- f\left(y(k), y(k-1),\cdots, y(k-n_y), u(k-1), u(k-1),\cdots, u(k-n_u)\right)\\ &+ f\left(y(k), y(k-1),\cdots, y(k-n_y), u(k-1), u(k-1),\cdots, u(k-n_u)\right)\\ &- f\left(y(k-1), y(k-2),\cdots, y(k-n_y-1), u(k-1), u(k-2),\cdots, u(k-n_u-1)\right)\end{aligned} \tag{6}$$

Set

$$\begin{aligned}\xi(k) &= f\left(y(k), y(k-1),\cdots, y(k-n_y), u(k-1), u(k-1),\cdots, u(k-n_u)\right)\\ &- f\left(y(k-1), y(k-2),\cdots, y(k-n_y-1), u(k-1), u(k-2),\cdots, u(k-n_u-1)\right)\end{aligned} \tag{7}$$

Using the Assumption A1 and differential mean value theorem, Eq. (7) can be rewritten as

$$\Delta y(k+1) = \frac{\partial f^*}{\partial u(k)}\left(u(k)-u(k-1)\right)+\xi(k) \tag{8}$$

where $\partial f^*/\partial u(k)$ denotes a partial derivative value of $f(.)$ respecting to $u(k)$ at certain time-point between $[u(k\text{-}1),u(k)]$.

Consider the following equation with a variable $\eta(k)$,

$$\xi(k) = \eta(k)\Delta u(k) \tag{9}$$

Since $|\Delta u(k)| \neq 0$, there must exist a unique solution $\eta(k)$ to Eq.(8).

Let $\phi(k) = \partial f^*/\partial u(k) + \eta(k)$. Then Eq.(8) is rewritten as $\Delta y(k+1)=\phi(k)\Delta u(k)$, which is the main conclusion of Theorem 1. And the boundedness of $\phi(k)$ is guaranteed directly by using Assumption A2.

**Remark 2:** Note that Eq.(4) is a dynamic linear system with slowly time-varying parameter when $\Delta u(k) \neq 0$ and $|\Delta u(k)|$ is not too big. To keep the rate of signal change, some parameters should be introduced into the criterion function except the condition $\Delta u(k) \neq 0$.

Another assumption is made for the system as follows.

**A3.** For all time instants k, the parameter $\phi(k)$ satisfies that $\phi(k) > \delta > 0$( or $\phi(k) < -\delta < 0$ ). Without loss of generality, $\phi(k) > \delta > 0$.

**Remark 3:** Assumption A3 is similar to the constraints on the control direction, which is a most common condition in the control system design and analysis. From a practical viewpoint, the HVDC system satisfies this assumption.

### 3.2. IMFAC DESIGNMENT

The iMFAC objective function is chosen as

$$J\left(u(k)\right) = \left(y^*(k+1)-y(k+1)\right)^2 + \lambda u(k)^2 \tag{10}$$

where $\lambda$ is penalty weight and $y^*(k+1)$ is the set-point.

Considering the Eq.(9), the system output $y(k+1)$ is

$$y(k+1) = y(k) + \varphi(k)\Delta u(k) \tag{11}$$

Substituting Eq.(11) into Eq.(10)

$$J(u(k)) = \left(y^*(k+1)-y(k)-\varphi(k)\left(u(k)-u(k-1)\right)\right)^2 + \lambda u(k)^2 \tag{12}$$

Set $\partial J(u(k))/\partial u(k) = 0$ and $u(k)$ is reformulated as:

$$u(k) = \frac{|\varphi(k)|^2}{\lambda+|\varphi(k)|^2}u(k-1) + \frac{\varphi(k)(y^*(k+1)-y(k))}{\lambda+|\varphi(k)|^2} \tag{13}$$

In order to have the generality of the algorithm Eq.(13) and make $u(k)$ change smoothly, a step-size constant series r is added in the second item,

$$u(k) = \frac{|\varphi(k)|^2}{\lambda+|\varphi(k)|^2}u(k-1) + \frac{\rho\varphi(k)(y^*(k+1)-y(k))}{\lambda+|\varphi(k)|^2} \tag{14}$$

where $\rho \in (0,1)$ is a step-size constant series.

**Remark 4:** From Eq.(10) and Eq.(14), we can see that $\lambda$ is not only a penalty factor on $u^2(k)$ , but also is a part of denominator in Eq.(14). This is an important parameter for this control system. A suitable $\lambda$ can improve the performance of the control system.

It can be seen that the $\phi(k)$ is unknown in Eq.(14) and the control input $u(k)$ cannot be calculated directly. Therefore, a new objective function is introduced as follows

$$J(\varphi(k)) = |y(k)-y(k-1)-\varphi(k)\Delta u(k-1)|^2 + \mu|\varphi(k)-\hat{\varphi}(k-1)|^2 \tag{15}$$

where $\mu>0$ is a weighting factor.

According to the optimal condition, estimation of $\phi(k)$ can be calculated using the iterative algorithm,

$$\hat{\varphi}(k)=\hat{\varphi}(k-1)+\frac{\eta\Delta u(k-1)}{\mu+\Delta u(k-1)^2}(\Delta y(k)-\hat{\varphi}(k-1)\Delta u(k-1)) \quad (16)$$

where η is positive constant denoting the step size, $(k)$ is the estimate of $\phi(k)$ .

Combined Eq.(14) and Eq.(16) together, the proposed improved MFAC scheme is as follows,

$$u(k)=\frac{|\hat{\varphi}(k)|^2}{\lambda+|\hat{\varphi}(k)|^2}u(k-1)+\frac{\rho\hat{\varphi}(k)(y^*(k+1)-y(k))}{\lambda+|\hat{\varphi}(k)|^2}$$

$$s.t.\begin{cases}\hat{\varphi}(k)=\hat{\varphi}(k-1)+\dfrac{\eta\Delta u(k-1)(\Delta y(k)-\hat{\varphi}(k-1)\Delta u(k-1))}{\mu+\|\Delta u(k-1)\|^2} \\ \hat{\varphi}(k)=\hat{\varphi}(1), \quad if \quad |\hat{\varphi}(k)|\le\varepsilon \quad or \quad \Delta u(k-1)\le\varepsilon\end{cases} \quad (17)$$

where the step-size series are usually set as ρ, ηÎ(0,1), λ, μ are two weighting factors, *e* is a positive constant with small value, and (1) is the initial value of $(k)$. The second constrain in Eq.(17) is a resetting algorithm which can keep iMFAC have a stronger ability to tracking time-varying $\phi(k)$.

**Theorem 2:** Given a nonlinear system Eq.(4) with Assumptions Al and A2, the set point $y^*(k+1)$=const, and suitable λ, ρ, μ, η, ε, the system output satisfies $\lim_{k\to\infty}\left(y^*(k)-y(k)\right)=0$ and using the iMFAC algorithm Eq.(16) and Eq.(17)

**Proof:** The similar proof can be founded in [23].

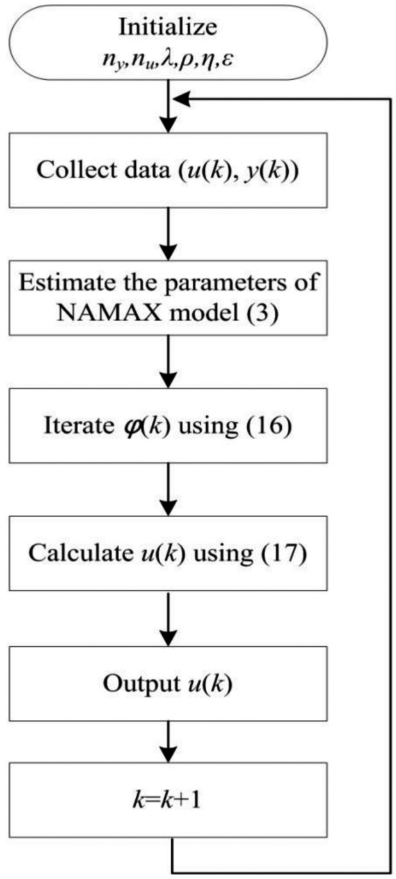
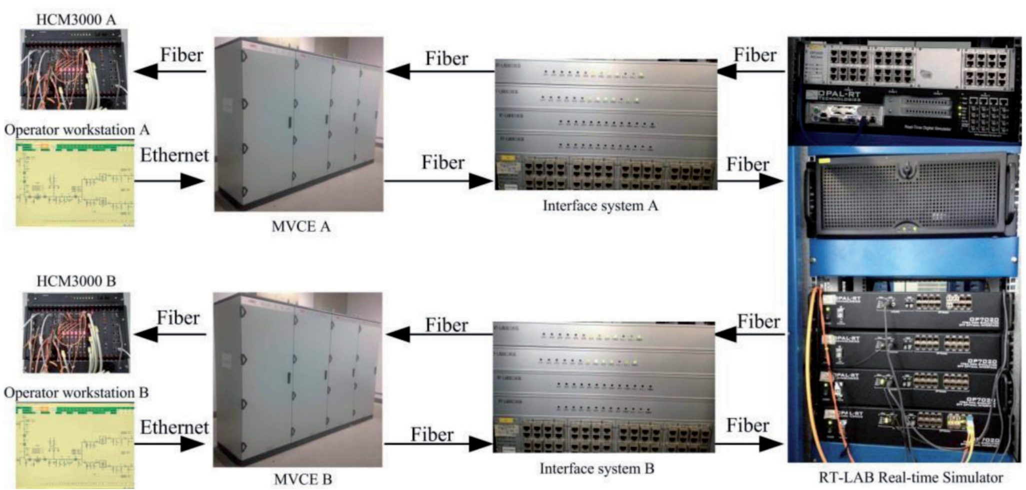



*Fig. 3: Flowchart of the proposed iMFAC*




*(a) The configuration of testing system*

*(b) The monitoring platform*

*Fig. 4: The testing system*

**Remark 5:** It should be noted that the iMFAC shown in Eq.(17) belongs to a kind of iterative algorithm, which don't need any structural information of VSC-HVDC system. Furthermore, the control input $u(k)$ is only determined using the collected input/output data of VSC-HVDC system. So iMFAC is regarded as a data-driven control approach and can overcome the un-modelled dynamics.

The procedures of the proposed iMFAC is summarized as follows (shown in Fig.3):

Step1: Initialize the parameters of $n_y$, $n_u$, λ, ρ, μ, η, ε.
Step2: Collect the input/output data $u(k)$, $y(k)$.
Step3: Estimate the parameters of system (4).
Step4: Iterate the parameter $\phi(k)$ using Eq.(16).
Step5: Calculate the output of iMFAC using Eq.(17).
Step6: Return step3.

## 4. EXPERIMENTS

To validate the established iMFAC, the Flexible-HVDC system with five terminals (Dinghai island, Daishan island, Qushan island, Sijiao island and Yangshan island) in Yangshan station located in Zhoushan was taken for the testing experiment. In this system, the DC voltage level is 200 *kV*, and the capacities of each terminal are as follows: 1) converter station in Dinghai 400MW, 2) converter station in Daishan 300MW, 3) converter station in Qunshan 100mW, 4) converter station in Sijiao 100MW, 5) converter station in Yangshan 100MW. The system included two control and protection systems named HCM3000, two modular valve control equipments (MVCE), two interface systems and RT_LAB software, which has been developed by XuJi Group Corporation located in Xuchang, China (shown in Fig.4).

The HCM3000 is mainly used to implement control and protection of Flexible-HVDC, which includes communication, recording event, outer loop voltage manipulation, inner loop current controlling, and sequence control interlock and so on. MVCEs generate the converter trigger pulse and protect parts of converter valve. Interface system is responsible for the protocol conversion and digital communication between HCM3000 and RT-LAB. RT-LAB is to build the model of valve and primary equipments, complete the function performance test (FPT) and dynamic performance test (DPT). The testing system has been completed in Yangshan station. Using the "Ziegler-Nichols" and "try and error" methods and the parameters of PI controller have been optimized during the functional tests.

To evaluate the effectiveness of the proposed algorithm, the iMFAC is introduced into the outer loop of the VSC-HVDC system in this section. The objective of the design is to adjust the active power (DC voltage or frequency) and reactive power, and set it as reference for the current controller in the inner loop. The controller's schematic of VSC-HVDC system is shown in Fig.5. Comparing to Fig.2, the PI controller is replaced by the iMFAC controller.

**Case I. Step in Active Power**

For iMFAC controller, the initial values were set as $y(1)=0.1$, $y(2)=0.1$, $y(3)=0.1$, $u(1)=u(2)=0$, (1)=0.01, and the controller parameters were set as $\varepsilon=10^{-5}$, $\eta=0.01$, $\rho=2$, $\mu=0.001$, $\lambda=0.5$. In this experiment, the output power was kept as 50MW. The step change in active power was set as 0.1pu, and the active power changed from 100MW to 90MW. The corresponding responses were shown in Fig.6. It is seen that the system works well even in case of change of direction of active power flow. There is a very small ripple in DC voltage during the transient in reactive power, which is again reflected in the d-current reference. Using the iMFAC controller, the overshoot and stabilization time were 10% and 20ms respectively (Fig.6(a)). In order to confirm the performance of iMFAC, the PI controller implemented in Yanshan station was taken for comparison.

$$u(t) = k_p e(t) + k_i \int e(t)dt \tag{18}$$

where $k_p$=0.3 and $k_i$=40. The results were shown in Fig.6(c) and Fig.6(d).

The overshoot and stabilization time of PI were 20% and 60ms. Comparing to the PI controller, the iMFAC has fast dy-

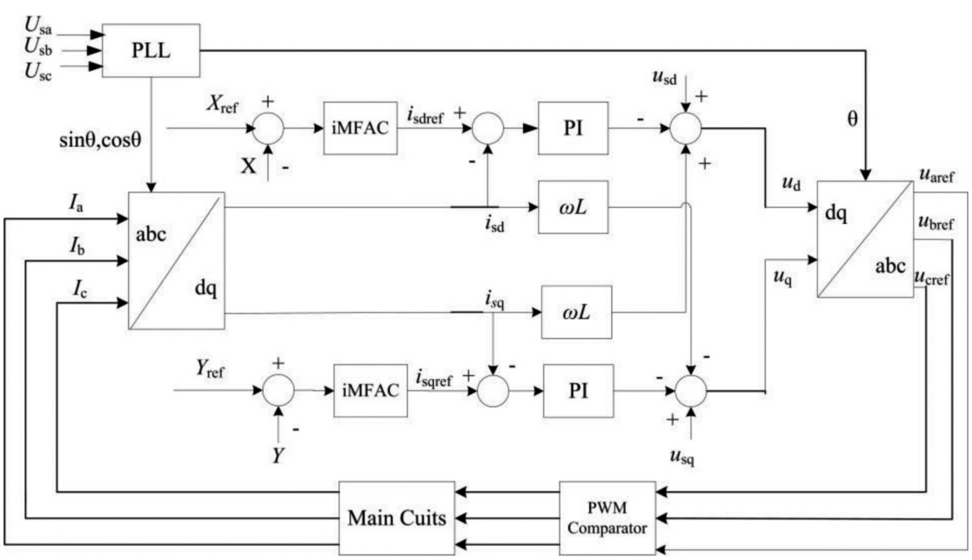



*Fig. 5: The schematic of VSC-HVDC system using iMFAC controller in the outer loop*

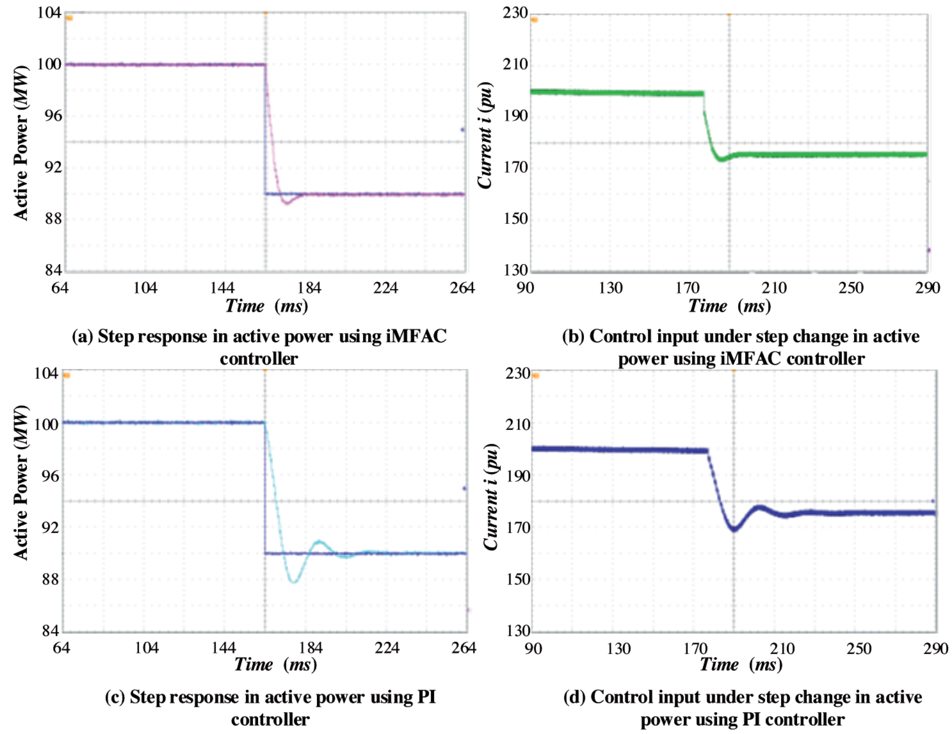



*Fig. 6: Step response in active power using different controllers*

namic response, small overshoot and low tuning time (shown in Table I).

| Methods | Overshoot | Stabilization Time |
|---|---|---|
| PI | 20% | 60ms |
| iMFAC | 10% | 20ms |

*Table I The indexes of the two methods*

**Case II. Disturbance in reactive power**

To test the robustness of iMFAC, the disturbance in reactive power was introduced into the VSC-HVDC system. The output power was preserved as 50MW. The disturbance with 0.02pu was added into DC, then DC changed from 188kV to 212kV (±12kV). The results were shown in Fig. 7 and Table II. The system works stably with the reversal of active power as well. The change in reactive power is reflected in d-com-

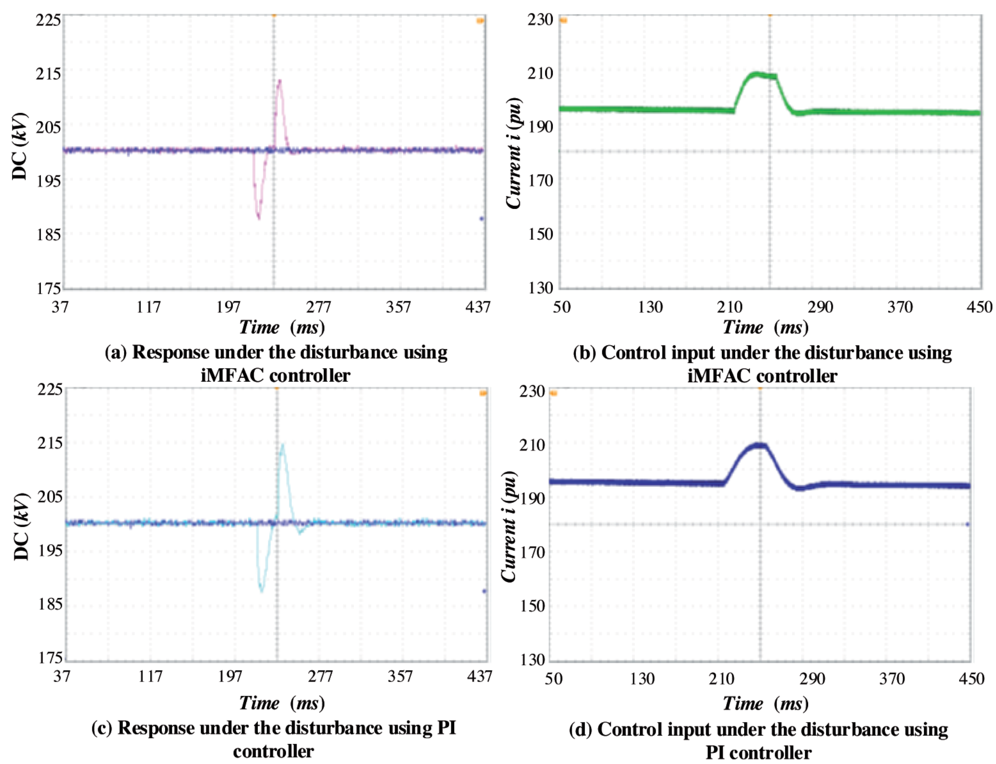



*Fig. 7: Response under the disturbance using different controllers*

ponent of current and the load current magnitude and direction. Because of the decoupling, almost no effect is observed in the control of active power. The dynamic response time of iMFAC was faster 20% than that of PI controller, and the amplitude of iMFAC was lower 10% than PI controller.

| Methods | Overshoot | Stabilization Time |
|---|---|---|
| PI | 25% | 40ms |
| iMFAC | 20% | 30ms |

*Table II  The indexes of the two methods*

Fig.8 showed the responses of iMFAC and PI under the disturbances with different amplitudes at different times. The average response velocity of iMFAC was faster 15% than that of PI controller (shown in Table III).

| Methods | Overshoot | Stabilization Time |
|---|---|---|
| PI | 15% | 30ms |
| iMFAC | 13% | 20ms |

*Table III  The indexes of the two methods*

From two case studies, it is shown that the system output can converge to the desired trajectory using the proposed iMFAC. Furthermore, the proposed algorithm can also restrain the measurement disturbance effectively.

## 5. CONCLUSION

In this paper, a novel improved model-free adaptive control (iMFAC) method is proposed to manipulate the active power of the converter station in the VSC-HVDC power transmission system. The advantage of the proposed algorithm is that the controller is designed using the input/output data directly and without requiring any structural information of VSC-HVDC system. The parameters of the iMFAC are auto-tuned online, which can achieve an ability to track the change of system. The mathematical analysis of iMFAC has proved the existence of solution.

Some aspects with the VSC-HVDC technology that were not taken to consideration and could be subject for future scope.

(1) Implementation of frequency control system. The frequency control is possible when the VSC is connected to weak network or passive loads, i.e the VSC is the main source of power. The frequency control in this case is obtain by varying the frequency of the valve pulse firing sequence in the PWM technique.
(2) VSC capability chart was not implemented. However its presence is very important since it prevents the station from working in overloading operation point
(3) Implementation of iMFAC to reduce or eliminate the harmonics, specially the second order harmonics on the DC voltage.
(4) Analysis the effect of linearization of the system, effect of DC system capacitance, AC filters and connection to weak AC system
(5) Verification of robustness of the controller through discrete time domain design and analysis.

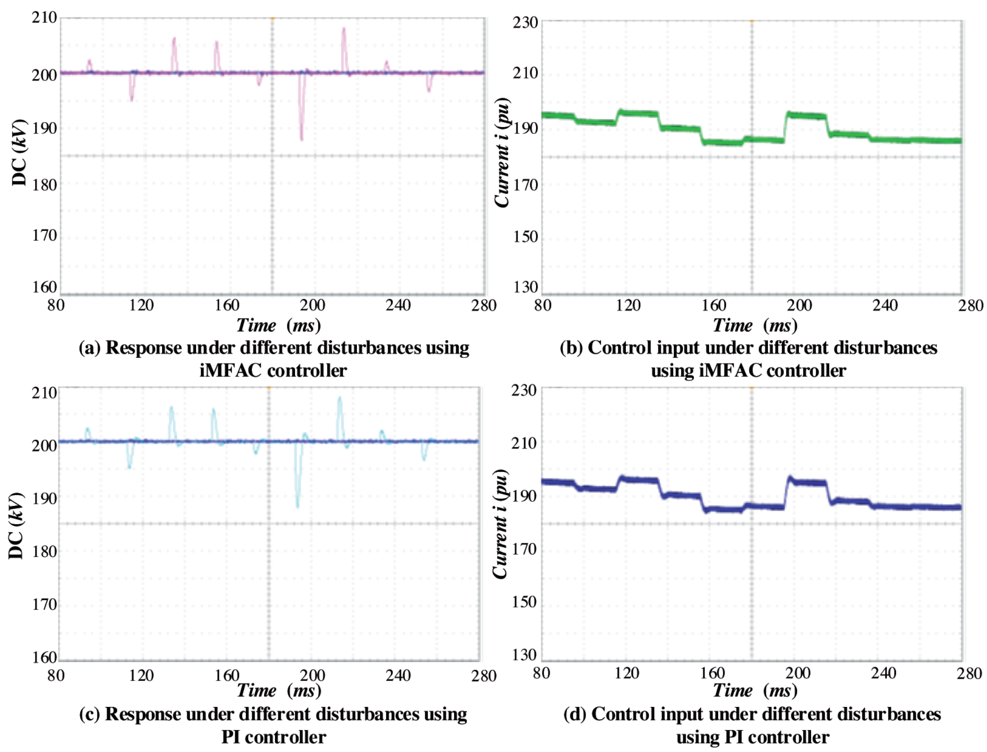



*Fig. 8: Response under different disturbances using different controllers*

## ACKNOWLEDGEMENT

The authors thank the financial support provided by the Science and Technique Plan Project of Henan Province [grant number 112101210700] and the National Nature Science Foundation of China [grant number 61273142, 51477070].

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