Emergency DC Power Support in Parallel AC/DC Power System

Xiangqiang Liu, Huifan Xie, Haijun Wang, Zhaoshuo Wang, and Jinzhuang Lv

Abstract Emergency DC Power Support (EDCPS for short) is an economical and practical emergency control measure to enhance the transient stability in parallel AC/DC power system and deserves further research. In this paper some research issues related to EDCPS in parallel AC/DC system are presented, including the mechanism of how EDCPS enhances transient stability in multi-machine system, the optimization of EDCPS strategy parameters and the effect of load characteristics on EDCPS strategy. As for online prediction control, an online preconceive calculation and real-time matching EDCPS control framework for China Sothern Power Gird is put forward, and as for time control for EDCPS, the optimal sequence time control theory is introduced, so is auto-disturbance rejection control theory. And finally the limitation for EDCPS is brought forward, and how to own a quick starting-time and quick DC power changing-rate deserves further research.

Keywords Parallel AC/DC system • Emergency DC power support • Online prediction control • Time-optimal control theory • Auto-disturbance rejection control theory

1 Introduction

With the complete implement of power supply strategy of "Nationwide Network Connection, Power Transmitted from West to East and Mutual Supply South and North", more and more HVDC projects will be put into practice in China network, and HVDC will lead a dominant role in that proposed power supply strategy.

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W. Wang (ed.), *Mechatronics and Automatic Control Systems*, Lecture Notes in Electrical Engineering 237, DOI 10.1007/978-3-319-01273-5_58,

Since it has a large transmission capacity and what's more, with 1.1 times' longtime overload-ability and 1.5 times' overload-ability for 3 s, HVDC can enhance transient stability after heavy disturbance in parallel AC/DC power grid. HVDC can quickly modulate both active and reactive power in a large scale, and when there exits heavy disturbance, those available HVDC systems can rapidly modulate active power into AC systems and finally compensate the power unbalance between the sending and receiving network, which is named Emergency DC Power Support [1, 2] (EDCPS for short), accordingly better last-low-voltage level or voltage vibrating conditions. EDCPS owns a great deal advantages, such as rapidity, reliability and great capacity, thence for the time being EDCPS has been an economical and practical emergency control measure and therefore deserves further research.

2 Study on Mechanism of Emergency DC Power Support

EEAC [3] is introduced to explain the mechanism of how EDCPS enhances transient stability by heavy disturbance in AC/DC power grid. After heavy disturbance, all generators in power grid can be divided into two groups, namely severely disturbed group (S group) and remnant group (R group), and then the whole system can be equaled into two-machine-unstable model. Considering that it is an unstable model of S group relative to R group, the whole system can be further equaled into One-Machine-Infinite-Bus system. In One-Machine-Infinite-Bus system, the DC power should be increased to make increasing area smaller than decreasing area, which will enhance transient stability, as illustrated in Fig. 1, and during the angle-swing-back course, DC power should be reduced to make increasing area smaller than decreasing area, which will better transient stability during swing-back course [5], as illustrated in Fig. 2.

3 Study on Emergency DC Power Support Strategies

Deep study has been done on Emergency DC Power Support Strategy, including the HVDC power support starting-time, the power support increment, the rising-rate and the lasting-time. The Yun-guang UHVDC Emergency DC Power Support Strategy in China Southern Power Grid of year 2010 is studied by PSD-BPA simulation tool, which is useful for power flow calculation and transient stability analysis. Study results show [4] that: DC power increment should be appropriate, bigger increment leads to bigger reactive power consumption, resulting in unfavorable effect on voltage recovery, while the power angle stability is enhanced; support starting- time should be proper, advanced start causes bigger reactive power consumption while delayed start may not provide enough accelerating area, as

Fig. 1 Swing-up course

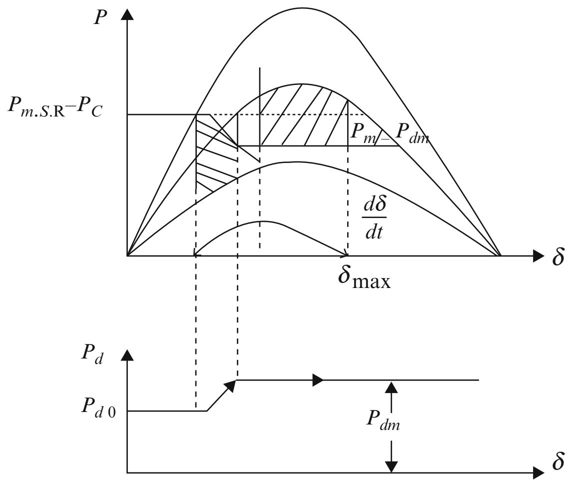
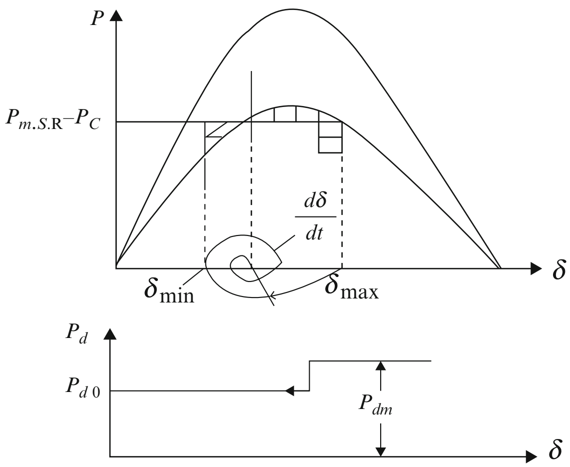


Fig. 2 Swing-back course



shown in Fig. 3; rising rate should not be too fast, otherwise reactive power consumption will increase and phase conversion voltage stability decrease; an appropriate DC power decrement during the swing-down of OMIB system power angle will enhance transient stability. After heavy disturbance, Emergency DC Power Support Strategy will take both angle stability and voltage stability into account, the HVDC power support starting-time, the power support increment, the rising-rate and the lasting-time all should be optimized.

Influence of load model on the Emergency DC Power Support Strategy is well analyzed. The impact of ZIP load (including constant -active-power-load, constant-current-load and constant-impedance-load), IM load (dynamic induction motor model), load composition, and load location of the specific CSG network on the EDCPS performance following large disturbances are studied by FASTEST tool,

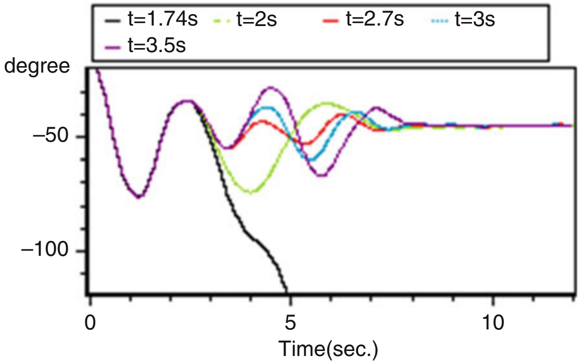


Fig. 3 Angle curve of Pinghai generator

which is useful for transient security quantitative analysis [5]. It is found that following a large disturbance, IM load absorbs more active power than ZIP load and the influence of the sending-end IM load on the post-fault EDCPS power-angel stability is completely opposite to that of receiving-end load. The sending-end loads are helpful to enhance the system stability. In the case that the sending-end load is smaller than the receiving-end load, synthesis load tends to deteriorate the post-fault EDCPS effect, and the active power support needs to be increased or provided in good advance.

IM model low-voltage response characteristic will deteriorate the EDCPS effect. Low voltage causes IM slip-ratio to increase, rotor equivalent resistance to decrease and stator current to increase so greatly that the absorbed reactive power increases too, which ultimately leads to low voltage because of lack of reactive power. In view of EEAC, the maximal value of electromagnetic power decreases and will reflect in the Power-Angel characteristic chart, which shows that the accelerating area increases and decreasing area decreases, and it is necessary for DC power to be increased to make accelerating area smaller and decreasing area bigger. What's more, the EDCPS starting-time should be appropriate, neither too early nor too late. If EDCPS starts too late, it can't provide enough decreasing area, and if EDCPS starts too early during voltage-dropping period, it will leads much more fluctuant to inverter commutation voltage and under the function of Voltage Depend Current Limiter Unit the actual DC power increment will be delayed and even be held back to drop. Figure 4 shows actual Yunnan-Guangdong UHVDC power by different Guangdong IM load proportions, with the function of Voltage Depend Current Limiter Unit the actual DC power can't reach the expected value 3,750 MW and after near 0.5 s the DC power drops to lower than 2,500 MW. It is easy to come to a conclusion from Fig. 4 that the bigger IM model proportions in Guangdong power grid the worse the power system stability.

Longer study reveals that with a timely EDCPS, an appropriate DC power rise and the corresponding rising rate in the first two up-swing courses, and with a suitable drop and the corresponding dropping rate in the first two back-swing courses, the transient stability is well imp roved. Moreover, by using the genetic-taboo searching algorithm, the modulation parameters are well optimized. Thus,

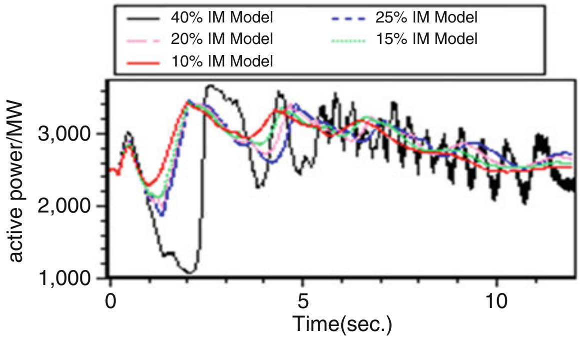


Fig. 4 Y/G DC power under different dynamic load proportions

according to the pre-set key power flow or the real-time power flow as well as the preconceive accident sets in the energy management system, the transient stability parameters of some serious preconceive accident sets can be calculated off line or on line in a certain operation mode. Case study indicates that the proposed EDCPS strategy effectively improves the transient stability of the power system.

4 Emergency DC Power Support Strategies Online Prediction Control

For emergency control framework of Online Preconceive Calculation and Real-time Matching, an Online Preconceive Calculation and Real-time Matching EDCPS Strategy [6] is put forward based on Integrated Extended Equal Area Criterion. The post-fault generators are firstly divided into two generator groups, namely severely disturbed group and remnant group, and then that proposed two groups are equated into One Machine Infinite Bus System. EDCPS strategies, including EDCPS starting-time, DC power rising-amount, rising and dropping ratio, are optimized by Enumeration Method with transient angle stability margin and transient voltage-drop acceptable margin as the objective index. EDCPS table can be made online in less than 5 min with the real-time data from Energy Management System (EMS for short).

Emergency DC Power Support function can quickly modulate available DC power when heavy fault occurs in parallel AC lines or other HVDC systems, and finally enhances transient stability with short-time DC overload capacity. Therefore, how to implement online EDCPS prediction by Wide Area Measurement System (WAMS for short) signals is of great significance and deserves to be researched. An online EDCPS prediction model based on WAMS signals is established for EDCPS online prediction control, and a newly structured Multi-resolution Analysis Orthogonal Wavelet Neural Network (MAOWNN for short) is constructed and applied to ECDPS prediction. The rotor speed and its corresponding changing-rate signals from generators near the available HVDC converter station are mapped by IEEAC as the characteristics signals for MAOWNN input, as formulas (1a and 1b), and the output of MAOWNN is the DC power rising-amount and its corresponding ratio. Adopting orthogonal scaling function as activation function, the proposed MAOWNN can converge fast and ensure the uniqueness of approximating function expression. Simulation results show that based on dimension-reduced principal components the MAOWNN can accurately give the controlled quantity of EDCPS.

$$\begin{cases} X = [X_{1,} X_{2,} \ldots X_{n,} X_{\Sigma}, \dot{X}_{\Sigma}] \\ X_n = \omega^1_{sa.n}, \omega^2_{sa.n}, \cdots, \omega^k_{sa.n} \\ X_{\Sigma} = \omega^1_{sa.\Sigma}, \omega^2_{sa.\Sigma}, \cdots, \omega^k_{sa.\Sigma} \end{cases} \tag{1a}$$

$$\begin{cases} \delta_{sa} = \sum\limits_{i \in s} M_i \delta_i / \sum\limits_{i \in s} M_i - \sum\limits_{j \in a} M_j \delta_j / \sum\limits_{j \in a} M_j \\ \omega_{sa} = \sum\limits_{i \in s} M_i \omega_i / \sum\limits_{i \in s} M_i - \sum\limits_{j \in a} M_j \omega_j / \sum\limits_{j \in a} M_j \\ \dot{\omega}_{sa} = \sum\limits_{i \in s} M_i \dot{\omega}_i / \sum\limits_{i \in s} M_i - \sum\limits_{j \in a} M_j \dot{\omega}_j / \sum\limits_{j \in a} M_j \end{cases} \tag{1b}$$

Where, s is the severely disturbed generator group near rectifier station, *a* is the remnant generator group neat inverter station, and k is the sampling points.

And the output of the DC power rising-amount and its corresponding ratio are shown as the following formula (2)

$$\begin{cases} \Delta P_d, \ \Delta P_d \in [0, 0.3, 0.5]\text{p.u.} \\ V_d, \ V_d \in [0, 999] MW/\min \end{cases} \tag{2}$$

5 Advanced Control Technology on Emergency DC Power Support

Advanced control technology is introduced to Emergency DC Power Support for better angle stability and voltage stability, and Time-optimal Control Theory [7] (TOC for short) is applied successfully.

Based on the equivalent-two-machine-two-area AC/DC parallel system, a TOC plane for second-order oscillation system is deduced, as shown in Fig. 5, and a TOC strategy for quickly suppressing inter-zone disturbance is proposed.

The second-order oscillation system TOC rule for an equivalent two-machine-two-area power system is deduced to determine when to raise DC power and when to drop DC power to quickly suppress disturbance, the rule is given in formula (3). Firstly TOC theory drives system state to a post-fault equilibrium point and Linear

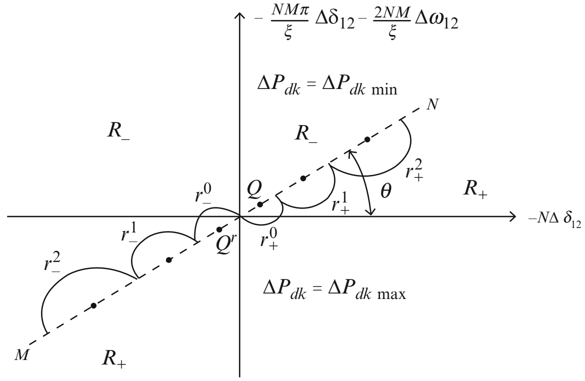


Fig. 5 Optimal switching curve plane

Quadratic Optimal Control (LQOC for short) theory is used to fix state in that equilibrium point. Switching curve is improved to avoid DC power jump-changing and to eliminate high-frequency nonlinear chattering and overshoot, and an optimal DC power control amount is calculated for fewest switching control. The proposed TOC strategy can well combine with the practical DC Emergency Run-up and Run-back control function effectively and quickly suppress inter-zone oscillation after first angle swing [8].

$$\Delta P_{dc}=\begin{cases}\Delta P_{dc.\max},\ if(-N\Delta\delta_{12},-\dfrac{NM\eta}{\xi}\Delta\delta_{12}-\dfrac{2NM}{\xi}\Delta\omega_{12})\in R^{+}\cup r^{+}\\ \Delta P_{dc.\min},\ if(-N\Delta\delta_{12},-\dfrac{NM\eta}{\xi}\Delta\delta_{12}-\dfrac{2NM}{\xi}\Delta\omega_{12})\in R^{-}\cup r^{-}\\ r^{+}=\bigcup\limits_{k=0}^{\infty}r_{+}^{k};r^{-}=\bigcup\limits_{k=0}^{\infty}r_{-}^{k}\end{cases}\quad(3)$$

Where, $\Delta P_{dc.\max}$ and $\Delta P_{dc.\min}$ are respectively the max DC power rising-amount and the max DC power decreasing-amount, and with the range $0<\Delta P_{dc.\max}\le 0.5$, $-0.5\le\Delta P_{dc.\min}\le 0$.

Auto-disturbance Rejection Control (ADRC for short) owns high adaptability and robustness and is also introduced.

Based on Time-optimal Control Theory and Auto-Disturbance Rejection Control theory [9] (ADRC for short), a new EDCPS control rule for quickly suppress disturbance in parallel AC/DC network is designed with WAMS signals.

TOC theory is introduced to drive and fix system state to a post-fault new equilibrium point which based on Integrated Extended Equal Area Criterion can be approached on-line with WAMS signals, and finally Auto-disturbance Rejection Control theory is introduced to trace the virtual control input. Simulation results of six-machine-dual-infeed three-area system show that the proposed EDCPSCS can take advantage of quick DC power modulation and short-time overload capability to provide emergency control and power support and has a better control effect than that of traditional linear DC power modulation. ADRC owns characteristics of high adaptability and robustness in disturbance and model uncertainty, moreover, control effect aimed at the new equilibrium point is better than that aimed at the original one [10].

6 Limitations and Difficulty of Emergency DC Power Support

HVDC owns 1.1 times' long-time overload-ability and 1.5 times' overload-ability for 3 s and can enhance transient stability after heavy disturbance in parallel AC/DC power grid. EDCPS owns a great deal of advantages, such as rapidity, reliability and great capacity, thence for the time being EDCPS has been an economical and practical emergency control measure. But there still exists some limitation and difficulty for EDCPS in practical HVDC. For example, firstly, the starting-time is not as quick as assumed because of AC filter's slow action; secondly, the DC power rising-rate and DC power decreasing-rate are lower than assumed, the max rates of HVDC power changing-rate in China Sothern Power Gird are both 999 MW per minute, and suck slow active power support makes no effect in transient stability. Hence how to own a quick starting-time and quick DC power changing-rate deserves further research.

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