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A Secondary Voltage Control Method for an AC/DC Coupled Transmission System Based on Model Predictive Control

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Abstract—**For an AC/DC coupled transmission system, the change of transmission power on the DC lines will significantly influence the AC systems' voltage. This paper describes a method to coordinated control the reactive power of power plants and shunt capacitors at DC converter stations nearby, in order to keep the voltage of the pilot bus tracking its set point considering the DC system's transmission schedule change. The approach is inspired by model predictive control (MPC) to compensate for predictable voltage change affected by DC side transmission power flow and the potential capacitor switching at DC converter stations. The control strategies are calculated from a multi-step dynamic optimization problem that is solved by mixed integer quadratic programming method. Time-domain simulations showed positive results of the proposed voltage controller.**

Index Terms—**HVDC system, Coordinated Voltage Control, Automatic Voltage Control, Model Predictive Control**

I. INTRODUCTION

In China, in order to avoid sub-synchronous resonance and other problems, HVDC systems have been used to transmit large quantity of power energy between different large AC systems. Some DC converter stations at receiving side are located far from load center, where the network is very weak. The change of the DC lines' transmission schedule, which may cause large variation of power flow, will result in violent voltage fluctuation inside AC systems. At the receiving side of HVDC system between northeast China power grid and north China power grid, Gaoling converter station discussed in this paper is just an example.

Secondary voltage controller, which aims to keep the voltage of pilot buses close to their references and distribute reactive power appropriately [1-3], has been widely applied in power system. The control interval is about 1-5 minutes that is restricted by communication conditions. However, traditional control method based on static optimization only concerns steady state information, so it doesn't always work well in an area containing DC converter stations since the shifting of DC operating mode could consequently lead to large active power flow changes. Furthermore, it is usually accompanied with automatic shunt capacitor switching inside the converter stations in only a few minutes, which may also cause reactive power change significantly and make the voltage much different from its last steady state.

The key to control voltage better in an area containing DC converter station at operating mode shifting period is to take the trend of transmission power flow and the consequent auto actions of the capacitors at the converter stations into consideration. Therefore, an MPC based method for secondary voltage control in an AC/DC coupled transmission system is proposed in this paper. MPC is an important method of process control theory, and has been applied to distribution networks voltage control [4-6], transmission voltage control [7], voltage stabilization under contingency [8-9], active power dispatch [10-11], energy storage management [12] and other fields and is showed to have good performance at coordinating different control units through the time.

The proposed method has some advantages comparing to the traditional one. Firstly, it concerns not only the present state but also the prediction states during a period of time in the future. That confirms an optimal control process of voltage. Secondly, predicted DC transmission power flow and behavior of shunt capacitors at converter stations are both considered, so it is possible to cooperate with power plants and the DC converter stations in the area. By the way, DC transmission power flow always changes according to a pre-defined schedule, so its predicted value could be exactly precise. Thirdly, voltage limits of all buses in the area are added to constraints, which assures the safety of the AC/DC system in a time-slot.

II. MODEL PREDICTIVE CONTROL

The proposed method concerns about the performance of system during N control circles in the future, and each control circle contains M predicted points as showed in Fig. 1. The value of DC power flow which changes according to pre-defined transmission schedule. Meanwhile, the behavior of shunt capacitors at the converter station also obeys fixed rules, which means a determined model can be built.
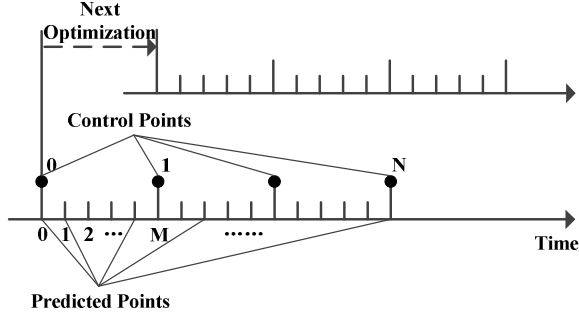
Figure 1. MPC Time Sequence

The first point of control sequence, the solution of optimization model, would be sent to each voltage control unit in the area according to MPC theory.

A. Objective

The voltage deviation of pilot buses is a key indicator of control system's performance. Thus the objective of optimization is showed as below.

$$\min_{V_G^{set}} \sum_{i=0}^{N-1} \sum_{j=0}^{M-1} \rho^{t_{i,j}} F_1 \tag{1}$$

In the equation above, optimization variables V_G^{set} is the set point of each generators' terminal voltage; $t_{i,j} = (Mi + j)\Delta t$ represents for the jth predicted point in the ith control period, and Δt is the interval between two predicted points; ρ is a decay coefficient with a value less than 1; F_1 stands for deviations between predicted values and the references of pilot buses at the typical time $t_{i,j}$, and the specific expression is showed as below.

$$F_1\left(t_{i,j}\right) = \sum_k \left[V_{Pilot,k}^{pre}\left(t_{i,j}\right) - V_{Pilot,k}^{ref} \right]^2 \tag{2}$$

$V_{Pilot,k}^{pre}$ and $V_{Pilot,k}^{ref}$ separately stand for the predicted voltage value and the reference of the kth pilot bus.

B. Constraints

i) Voltage prediction can be obtained by solving power flow sensitivity equations.

$$\begin{bmatrix} V_G^{set}\left(t_{i,j}\right)-V_G^{set}\left(t_{0,0}\right) \\ V_{Pilot}^{pre}\left(t_{i,j}\right)-V_{Pilot}^{pre}\left(t_{0,0}\right) \\ V_{St}^{pre}\left(t_{i,j}\right)-V_{St}^{pre}\left(t_{0,0}\right) \\ V_{Other}^{pre}\left(t_{i,j}\right)-V_{Other}^{pre}\left(t_{0,0}\right) \end{bmatrix} = S \begin{bmatrix} P_G^{pre}\left(t_{i,j}\right)-P_G^{pre}\left(t_{0,0}\right) \\ Q_G^{pre}\left(t_{i,j}\right)-Q_G^{pre}\left(t_{0,0}\right) \\ P_{St}^{pre}\left(t_{i,j}\right)-P_{St}^{pre}\left(t_{0,0}\right) \\ Q_{St}^{pre}\left(t_{i,j}\right)-Q_{St}^{pre}\left(t_{0,0}\right)+Q_{St}^C\left[N_{St}^{pre}\left(t_{i,j}\right)-N_{St}^{pre}\left(t_{0,0}\right)\right] \end{bmatrix} \tag{3}$$

Here V_G^{set} is the vector of generator terminal voltages' set values, V_{Pilot}^{pre} is the vector of predicted pilot buses' voltages, V_{St}^{pre} is the vector of predicted converter stations' bus voltages, and V_{Other}^{pre} is the vector of other buses' voltages. S is the sensitivity matrix of bus voltage to injected power flow. P_G^{pre}

and Q_G^{pre} are separately the vector of predicted values of generators' active and reactive powers. P_{St}^{pre} and Q_{St}^{pre} are that of DC transmission power flow, which can be precisely obtained according to their pre-defined transmission schedules. $Q_{St}^C = diag\begin{bmatrix} Q_{St,1}^C & Q_{St,2}^C & \cdots \end{bmatrix}$ represents the capacity of a single capacitor in converter stations, while N_{St}^{pre} stands for the number of capacitors connected to the network.

ii) In order to trigger the switching event of a capacitor, the voltage at the time just before the switching event should be obtained as a judgment. It can be deduced in the same way using sensitivity equations.

$$\begin{bmatrix} V_G^{set}\left(t_{i,j}\right)-V_G^{set}\left(t_{0,0}\right) \\ \hat{V}_{Pilot}^{pre}\left(t_{i,j}\right)-\hat{V}_{Pilot}^{pre}\left(t_{0,0}\right) \\ \hat{V}_{St}^{pre}\left(t_{i,j}\right)-\hat{V}_{St}^{pre}\left(t_{0,0}\right) \\ \hat{V}_{Other}^{pre}\left(t_{i,j}\right)-\hat{V}_{Other}^{pre}\left(t_{0,0}\right) \end{bmatrix} = S \begin{bmatrix} P_G^{pre}\left(t_{i,j}\right)-P_G^{pre}\left(t_{0,0}\right) \\ \hat{Q}_G^{pre}\left(t_{i,j}\right)-\hat{Q}_G^{pre}\left(t_{0,0}\right) \\ P_{St}^{pre}\left(t_{i,j}\right)-P_{St}^{pre}\left(t_{0,0}\right) \\ Q_{St}^{pre}\left(t_{i,j}\right)-Q_{St}^{pre}\left(t_{0,0}\right)+Q_{St}^C\left[N_{St}^{pre}\left(t_{i,j-1}\right)-N_{St}^{pre}\left(t_{0,0}\right)\right] \end{bmatrix} \tag{4}$$

Here $\hat{V}_{Pilot}^{pre}$ is the vector of predicted pilot buses' voltages, $\hat{V}_{St}^{pre}$ is the vector of predicted converter stations' bus voltages, and $\hat{V}_{Other}^{pre}$ is the vector of other buses' voltages at that time. $\hat{Q}_G^{pre}$ is correspondingly the vector of predicted values of generators' reactive powers.

iii) Shunt capacitors' switching rules.

$$N_{St}^{pre}\left(t_{i,j}\right) = \begin{cases} N_{St}^{pre}\left(t_{i,j-1}\right)-1, \hat{V}_{St}^{pre} > V_{St}^{max} \\ N_{St}^{pre}\left(t_{i,j-1}\right)+1, \hat{V}_{St}^{pre} < V_{St}^{min} \\ N_{St}^{pre}\left(t_{i,j-1}\right), else \end{cases} \tag{5}$$

There is a set of rules for shunt capacitors at the converter station under voltage control mode. When the voltage of a converter station exceeds its upper or lower bound $V_{St}^{max} / V_{St}^{min}$, a capacitor will be put into or cut off from the grid. Besides, there are also rules under other kinds of station control mode such as reactive control mode, under which voltage bounds are taken place by reactive power bounds. Logical constraints in equation 5 can be transferred into mix integer form as showed below.

$$\begin{cases} N_{St}^{pre}\left(t_{i,j}\right) = N_{St}^{pre}\left(t_{i,j-1}\right)-Ct_{St}^{pre}\left(t_{i,j}\right)+Pt_{St}^{pre}\left(t_{i,j}\right) \\ \left(Ct_{St}^{pre}-1\right)R < \hat{V}_{St}^{pre}-V_{St}^{max} < Ct_{St}^{pre}R \\ \left(Pt_{St}^{pre}-1\right)R < V_{St}^{min}-\hat{V}_{St}^{pre} < Pt_{St}^{pre}R \end{cases} \tag{6}$$

Ct_{St}^{pre} and Pt_{St}^{pre} are both 0-1 variables, while R is a big positive number.

iv) Shunt capacitors in a converter station should not be frequently switched, since it may cause damage to both the capacitors and power system. Therefore, the constraints of switching times are set.

$$\begin{cases} O_{St}^{pre}\left(t_{i,j}\right) = Ct_{St}^{pre}\left(t_{i,j}\right) + Pt_{St}^{pre}\left(t_{i,j}\right) \\ \sum_{i=0}^{N-1}\sum_{j=0}^{M-1} O_{St}^{pre}\left(t_{i,j}\right)_1 \le O_{St}^{max} \end{cases} \quad (7)$$

Apparently O_{St}^{pre} is a 0-1 variable representing the action of capacitors, while O_{St}^{max} is the limit of switching times.

v) Operating limits of system including that of bus voltages, generator reactive powers and numbers of shunt capacitors in converter stations.

$$\begin{bmatrix} V_G^{min} \\ V_{Pilot}^{min} \\ V_{St}^{min} \\ V_{Other}^{min} \\ Q_G^{min} \\ N_{St}^{min} \end{bmatrix} \le \begin{bmatrix} V_G^{set} \\ V_{Pilot}^{pre} \\ V_{St}^{pre} \\ V_{Other}^{pre} \\ Q_G^{set} \\ N_{St}^{pre} \end{bmatrix} \le \begin{bmatrix} V_G^{max} \\ V_{Pilot}^{max} \\ V_{St}^{max} \\ V_{Other}^{max} \\ Q_G^{max} \\ N_{St}^{max} \end{bmatrix} \quad (8)$$

C. Solving Algorithm

Expressions 1-4 and 6-8 compose the whole optimizing model of the secondary voltage controller in the AC/DC coupled transmission system. It is a mix integer quadratic programming problem, which can be solved by dual simplex algorithm accompanied with branch-and-bound method.

III. SIMULATION RESULTS

A. Simulation System

The simulation system is built based on the north China power grid, and use the history data of it in Oct. 25th 2013 as input data. The secondary voltage control with a 5 minute cycle is restricted to an area showed in Fig. 2. High voltage bus of TM Station is selected as the pilot bus. In the simulation, the reference value of pilot bus voltage is set to 520 kV, while the upper and lower voltage bounds that trigger switching events of capacitors at the converter station are separately 534 kV and 518 kV. Parameters N and M are separately set to 2 and 5, so that the MPC optimization time slot is 10 minute wide, and the interval of predictions Δt is 1 minute.
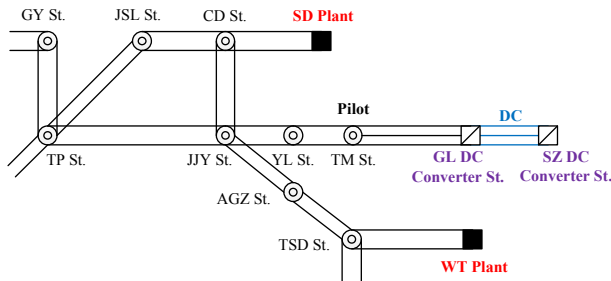

Figure 2. Secondary Voltage Control Area

Since the problem discussed doesn't refer to transient process, a power flow calculation program is used to simulate the changing states of the system. The solving of optimization model is carried out by CPLEX.

B. DC Transmission Power Decreasing

DC transmission power starts to decrease at 1:00 a.m. from about 3000 MW to 2100 MW at a speed of -30 MW/min, as showed in Fig. 3. This results in voltages of nearby buses' increasing and shunt capacitors' being cut down at the converter station.
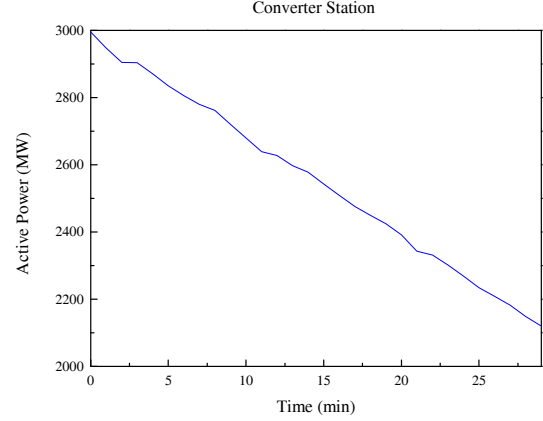

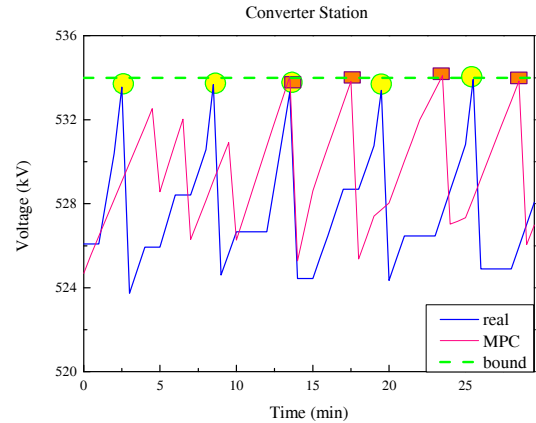Figure 3. Active Power of DC Transmission Line

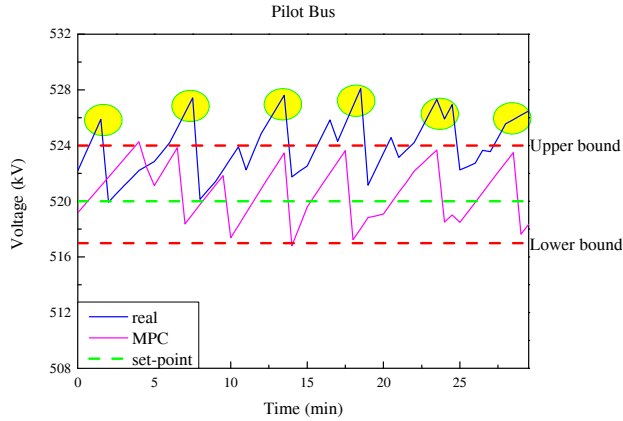

Figure 4. Converter Station Voltage
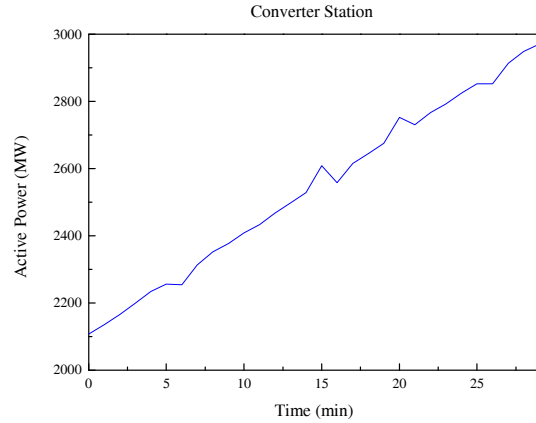
Figure 5. Pilot Bus Voltage

Figure 6. Active Power of DC Transmission Line

Fig. 4 and Fig. 5 separately show the voltage value of the converter station and the pilot bus. We can see in Fig. 4, yellow circles and orange squares stand for switching events under traditional and MPC controller. With the MPC based method, switching times of capacitors is lesser. Meanwhile, Fig. 5 illustrates that controller using proposed method keeps the voltage of pilot bus staying in the safe range, but the traditional controller doesn't always do (yellow circles). In fact with the MPC method, the system realizes that alongside with the decreasing of DC transmission power, voltage of the converter station has to reach its upper bound to trigger switching of capacitors. The voltage drop between the DC converter station and the pilot bus station is determined by the active and reactive power transferred between them which are strongly related with the DC power flow and the number of capacitors connected with the grid. The effect of DC power flow on voltage drop would more or less be offset regularly by capacitors. Thus, power plants will adjust their reactive power in advance to affect the switching time of capacitors, in order to enlarge the voltage drop and reduce the voltage value of the pilot bus at that time.

C. DC Transmission Power Increasing

DC transmission power starts to increase at 4:45 a.m. from about 2100 MW to 3000 MW at a speed of 30 MW/min, as showed in Fig. 6. This results in voltages of nearby buses' decreasing and shunt capacitors' being put into the power grid at the converter station.
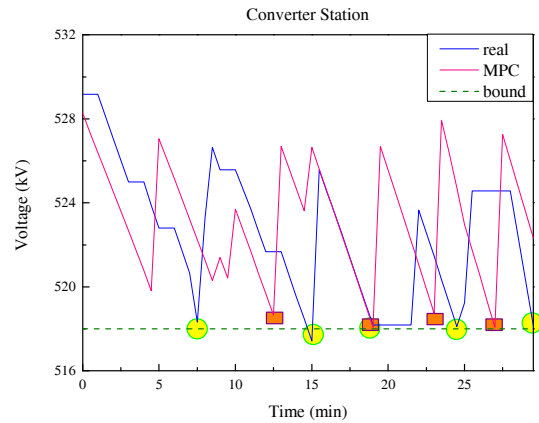

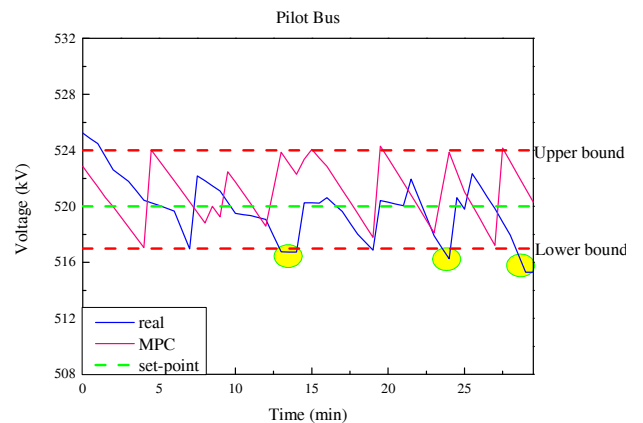
Figure 7. Converter Station Voltage

Figure 8. Pilot Bus Voltage

Fig. 7 and Fig. 8 separately show the voltage value of the converter station and the pilot bus. We can see in Fig. 7, yellow circles and orange squares stand for switching events

under traditional and MPC controller. With the MPC based method, switching times of capacitors is lesser. Meanwhile, Fig. 8 illustrates that controller using proposed method keeps the voltage of pilot bus staying in the safe range, but the traditional controller doesn't always do (yellow circles). In fact with the MPC method, the system realizes that alongside with the increasing of DC transmission power, voltage of the converter station has to reach its lower bound to trigger switching of capacitors. Thus, power plants will adjust their reactive power in advance to affect the switching time of capacitors, in order to lessen the voltage drop and increase the voltage value of the pilot bus at that time.

IV. CONCLUSIONS

An MPC based secondary voltage control method is proposed in this paper. Here, what we predict include two parts, first is the active power variation trend according to the pre-defined transmission schedule of DC lines, and second is the reactive power variation trend considering the consequent auto-actions of shunt capacitors at converter stations. Based on the proposed dynamic programming problem, the control performances not only for the current snapshot but also for a future time-slot are optimized. In an AC/DC coupled area, especially where the DC lines feed into a relatively weak AC areas, it is proved that the proposed voltage control method would assure better voltage profiles.

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BIOGRAPHIES

Fengda Xu was born in Zhenjiang City, Jiangsu Province in China on Nov. 30, 1989. He obtained his B. Eng. in Electronic Engineering from Tsinghua University, Beijing, China, in 2012. He is currently studying towards his PhD in Automatic Voltage Control, specializing in Power System Automation at Tsinghua University (THU), Beijing, China. His current research interests include the automatic voltage control, integration of renewable generation on the power system, model predictive control and smart grids.

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Hongbin Sun (SM'12) received the double B.S. degrees from Tsinghua University, Beijing, China, in 1992 and the Ph.D. degree from the Department of Electrical Engineering, Tsinghua University in 1997. He is now Changjiang Chair Professor of Education Ministry of China, Full Professor of electrical engineering in Tsinghua University and Assistant Director of State Key Laboratory of Power Systems in China. From 2007 to 2008, he was a Visiting Professor with School of Electrical Engineering and Computer Science, Washington State University, Pullman, WA, USA. In the last 15 years, he has developed a commercial system-wide automatic voltage control systems which has been applied to more than 20 large-scale power grids in China. He published more than 200 academic papers. He held more than 20 patents in China.
　Prof. Sun is an IET Fellow, members of IEEE PES CAMS Cascading Failure Task Force and CIGRE C2.13 Task Force on Voltage/Var support in System Operations. He won the China National Technology Innovation Award for his contribution on successful development and applications of New Generation of EMS for Power Systems in 2008, the National Distinguished Teacher Award in China for his contribution on power engineering education in 2009, and the National Science Fund for Distinguished Young Scholars of China for his contribution on power system operation and control in 2010.

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