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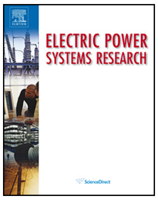

Automatic voltage control system with market price employing large wind farms

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ABSTRACT

The automatic voltage control (AVC) system is typically to minimize the grid loss while maintaining the voltage magnitude in an acceptable operational band. Being a market-driven power system, the power loss is normally purchased based on the market price. This paper proposes an approach for the Danish AVC system to couple the automatic voltage control (AVC) system to the market price in order to accurately assess the operational cost, where the objective is to minimize the total operational cost including the grid loss, the shunt switching cost, the transformer tap change cost and the cost of the voltage control service provided by the power plant owners. The benefit of employing the large offshore wind farms in this AVC system is investigated. The simulation based on the measurement data from the Danish electricity control center demonstrates the superiority of the proposed approach in terms of the cost minimization. The gained profit by employing the wind farms can be an argument to purchase the voltage control service provided by these wind farms.

1. Introduction

Wind energy is on the rise all over the world. In the Danish power system, wind energy covered 42% of the annual demand in 2015, aiming at 50% by 2020. Until recently, the continuous voltage control was provided by thermal power stations. However, as wind power penetration increases, there are many hours where the thermal power stations are not in operation. Consequently, the system may lose the continuous voltage control ability delivered by thermal power stations. In addition, the Danish interconnection capacities increase causing more volatile power flows. The rapid power changes on the interconnectors required by the market and the lack of continuous voltage control due to decommissioning of thermal power stations call for a redesign of the voltage control system in the Danish transmission grid. According to the Danish grid development plan, many switchable and tap-able inductive shunts will be placed in the grid and this new source of reactive power will be integrated in the overall voltage control system. The cost of switching these discrete components in the voltage control system is estimated to be significant and should be considered in the decision making process.

Since 1980s, the first AVC system established in Franc [1,2], the synchronous generators, equipped with excitation systems, are typically the backbone of the control system due to their relatively large sizes of the reactive power source and the short response time on the disturbances [3–7]. The shunt compensators and the transformer taps are primarily controlled to assist the synchronous generators in reserving their reactive power regulation capacity. The entire system is typically split into multiple zones, where a pilot bus is defined in each zone. The condition of the voltage magnitude in each zone is assembly represented at the pilot bus. The objective of the AVC system in each zone is to maintain the voltage at the pilot bus within the acceptable band. In addition to maintaining the voltage at the pilot bus, the voltage control system should ensure the sufficient reactive power reserve in each zone. The voltage set-points are thus dispatched from the zonal controllers to the assigned power plants equipped with the plant controllers. The plant controllers will further convert the voltage set-points to the reactive power set-points to the individual generators [3,4]. On top of zonal controllers, the national controller focuses on the economic operation, e.g. minimizing the grid loss of the overall system [3,4]. This is so called hierarchical structure based AVC system. The whole power system is capable of efficiently being controlled with limited information i.e. focusing on control the pilot bus voltage. In the relative small system, e.g. the Danish transmission system, it is preferable to use centralized AVC, where the control center

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Nomenclature

Variables

v_f, v_t	Sending and the receiving ends voltages
τ, ϑ	Transformer tap ratio and phase shift angle
V_{trf}	Transformer primary side voltage magnitude
V_{sh}	Shunt terminal voltage magnitude
b	Shunt susceptance
Q_g	Generator reactive power output
V, δ	Voltage magnitude and angle
M	Absolute of tap ratio change
Z	Absolute of shunt susceptance change
Y	Absolute of generator reactive power output
x_z	Discrete variable

Parameters and derived variables

P_{br}	Branch series loss
R_s, X_s	Series resistance and the reactance
N_{br}	Total number of branches
e^j	Exponential operator
$\mathcal{L}$	Branch set
P_{tr}	Transformer no-load loss
N_{tr}	Total number of transformers
G_{tr}	Conductance of transformer core
$\mathcal{T}$	Tap-able transformer set
P_{sh}	Reactor loss
N_{sh}	Number of reactors
G_{sh}	Conductance of reactor
$\mathcal{B}$	Switchable shunt set
C_p	Total grid loss cost
λ^d	Market price
d	Index of price corresponding to AVC loop
C_τ	Total cost of tap ratio changes
p_τ	Cost of tap ratio change
N_τ	Total number of tap-able transformers
τ^0	Initial tap ratio of a transformer
C_b	Total cost of shunt susceptance changes
p_b	Cost of shunt susceptance change
b^0	Initial shunt susceptance
N_b	Total number of shunts
C_g	Total cost of generator reactive power output
p_Q	Cost of generator reactive power output
$\mathcal{G}$	Generator set
N_g	Total number of generators
i, k	Indices of elements in a set
G, B	Conductance and the susceptance
P_l, Q_l	Active power and reactive power loads
P_G, Q_G	Active power and reactive power generations
$\mathcal{V}$	Busbar set
$\{ref\}$	Reference busbar set
$V_{\min}$, $V_{\max}$	Min. and max. voltage magnitude
$b_{\min}$, $b_{\max}$	Min. and max. susceptance of shunt
$\tau_{\min}$, $\tau_{\max}$	Min. and max. tap ratio of transformer
$Q_{g\min}$, $Q_{g\max}$	Min., max. of generator reactive power limit
$M_{\max}$	Max. absolute of tap ratio change
$Z_{\max}$	Max. absolute of shunt susceptance change
$M_{tot\_\max}$	Total tap ratio change
$Z_{tot\_\max}$	Total shunt susceptance change
$x_{z\max}$, $x_{z\min}$	Max. and min. limits of discrete variables
γ_k	Penalty factor at iteration k
K	Parameter for increasing γ at each iteration
N_z	Total number of discrete variables

Abbreviations

AVC	Automatic voltage control
POC	Point of connection
TSO	Transmission system operator
PCC	Point of common coupling
ORPF	Optimal reactive power flow
VSC	Voltage source converter
LCC	Line-commutated
HVDC	High-voltage direct current
OLTC	On-load tap changer
SCADA	Supervisory control and data acquisition
SE	State estimator
EMS	Energy management system
PDIPM	Primal-dual interior point method
CHP	Combined heat and power plants

dispatches the set-points to all assigned components to minimize the operational cost while maintaining the voltage for all buses within an acceptable band [8,9].

Being a market-driven system from 2000, the installed wind power capacity in Denmark is doubled, i.e. from 2400 MW in 2000 to 5000 MW by 2015. The market is considered to be an essential tool to integrate such a large amount of wind power. It provides a common platform for all market players to balance the system including the fluctuated wind power. In addition, it balances the production and consumption over large geographic areas, e.g. using the hydro power in Norway as storage to compensate the intermittence of the Danish wind power via the market. The Danish system is therefore very flexible, where the transits in the main corridors can change significantly and even reverse the flow direction within few hours. The electricity price varies to reflect the balance of the production and consumption. The voltage control in this system to minimize the operational cost, may not really reduce the cost, as the price of the grid loss can be very small or even negative while the regulation cost of the reactive power components are constant.

In the current Danish system, the reactive power regulation capability of large offshore wind farms is not applied to control the system voltage. These wind farms connect to the onshore transmission grid over long cables. The voltage control ability is therefore limited by the long cables [10]. If the wind turbines are Type I, then continuous reactive power component, e.g. Static Var Compensation, may be needed onshore to smoothly control the voltage according to the intermittent wind power production. The modern wind farms, constructed with Type III or Type IV wind turbines, are capable of fast regulating the reactive power output to control the system voltage. For such modern wind farms, reactor banks are typically placed onshore to compensate the cables according to the loadings. As the central power plants are gradually decommissioning, the utilization of the reactive power from the large offshore wind farms regained the attention. They are expected to participate in the coordinated voltage control system to enhance the overall system control ability. However, a decision making algorithm is needed to firstly assess the benefit to employ the wind farms for the voltage control purpose considering different operational limitations.

The key contributions of this paper are summarized as follows. First, a decision making algorithm for the AVC system is proposed. The objective is formulated to minimize the total system operational cost including the grid loss cost, the shunt switching cost, the transformer tap change cost and the generator reactive power cost. All costs are converted in terms of monetary, where the electricity market price is associated to the grid loss, and the regulation cost for each component is estimated. Moreover, the problem is formulated in the nonlinear programming framework, where all discrete variables are treated as continuous variables, and then the