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Automatic Voltage Control (AVC) of Danish Transmission System - Concept Design

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SUMMARY

For more than 20 years it has been a consistent plan by all Danish governments to turn the Danish power production away from fossil fuels towards renewable energy. The result today is that 37% of the total Danish power consumption was covered by mainly wind energy in 2013 aiming at 50% by 2020. Another consequence is the public way of generally thinking green which have led to a national decision of undergrounding not only all of the Danish distribution system but also the future transmission system. These issues initiate the infrastructure constructions of the transmission system i.e. a large amount of overhead lines over 100 kV as well as the new planed transmission lines will be undergrounded; the transfer capacities will be enlarged by upgrading the interconnections. Large amounts of reactive power components will be placed in the system partly for cable compensation and partly for voltage security. Consequently, the ramping speed of the transits in the main corridors via the interconnections is foreseen to be increased. The voltage control based on the present system is thus becoming a challenging objective. This survey paper presents some of the existing AVC systems i.e. system structures, objectives, constraints, algorithms for optimal power flow and some special functions in particular systems, which inspires the concept design of a Danish AVC system to address the future challenges of voltage control. In the concept, the Danish AVC design is based on a centralized control scheme. All the buses are monitored where the voltage magnitudes are maintained continually. The loss minimization including switching cost is the objectives of the AVC system. The reactive power reserves as constraints are taken into account to limit the regulation capabilities of generators. The Day ahead and short-term forecast is to be implemented to reduce the working load of the real time system, as well as to minimize the numbers of switching times of the discrete components. The fallback controllers are to be installed in selected substations to enhance the system reliability and the robustness in case the substation loses the telecommunications to the control center. RPCs will be integrated to the AVC system as normative regulators in the later stage. Distributed generation units can be organized as virtual power plants and participate in voltage control at transmission level. Energinet.dk as the Danish TSO will implement the first stage of the AVC system by 2016.

KEYWORDS

Voltage control - Hierarchical control - Centralized Control - Optimal power flow

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I. INTRODUCTION

The Danish power system is a transit-dominated system, which connects the Nordic and the continental European systems as a hub of electricity transmission. The total amount of transfer capacity over the borders is about 5000/6000 MW import/export today that is closed to the peak demand inland, 6400 MW. The large transit power on the transmission lines can introduce significant voltage variations, which requires adjusting the reactive power flow to maintain voltage operating limits. Most of the Danish interconnections are established as HVDC links during the past 40 years. Nowadays, the ramping speed for the HVDC links limits the changing of transit power to 30 MW/min per HVDC link. One of the main reasons is to provide the operators enough time to control the voltage by adjusting the reactive power components manually.

The penetration of wind energy is continually increasing in the Danish power system. The share of wind energy on covering the demand was 33.2% in 2013 and will be increased to 50% by 2020 [1]. Several new large offshore wind power plants will be built, which connects to land over long submarine AC cables. The conventional central power plants equipped with excitation system for voltage support are thus being forced out of the market. Consequently, the system loses the continuous reactive power source used for voltage control. Therefore, the voltage control in the future grid will be supported by ancillary components e.g. synchronous condenser, SVC, StatCom and the renewable energy based production units. In addition, as the central power plants are out of service, the power may flow from distribution levels to the transmission level. This suggests that the pre-defined transmission pattern is changing significantly. In order to fulfill the characteristics and the new requirements of the future system, some questions should be addressed.

1) *Reactive power reserve*

Among the present wind turbines in Denmark, nearly 70% of the installed capacity is of the 'Danish concept' type i.e. fixed speed wind turbines with asynchronous generators directly connect to the grid (type 1), which require reactive power support after a voltage dip. As central power plants are being forced out of service, the system may potentially lack of the reactive power resource required to support the voltage in emergency situations. Therefore, it is necessary to maintain sufficient reactive power reserves in the continuous reactive power sources, e.g. the synchronous condenser and StatCom, to support the voltage in emergency situations.

2) *Coordinate the voltage control*

The conventional power plants continuously control the voltage smoothly with the Automatic Voltage Regulator devices (AVR). In contrast, shunts and taps of transformers with a certain size represent a type of discrete regulation devices that introduce step-wise voltage changes. As central power plants are decommissioned, the short-circuit capacity of the system will be lower. In this case, an adjustment of the reactive power flow on a control device may result in an unacceptable voltage change. This may lead to cascading adjustments on many control devices. In some cases, inappropriate adjustments will result in voltage collapse [2].

In the Danish grid, many discrete reactive power components that normally control the reactive power flow on the branches are partially autonomous via local Reactive Power Control (RPC) devices. These RPCs are mainly located in the HVDC stations to compensate the reactive power consumption by coupling the filters. The control center can thus adjust the set point at RPCs through remote control. The voltage control should take into account the impacts from the filters, especially in the cases where the short-circuit capacity is low, and hence where the voltage changes significantly after the filter is cut in/out. Therefore, a coordinated control scheme should maintain the voltage and be capable of regulating the control devices with as few adjustments as possible [3]. Moreover, it should reduce the system loss by minimizing the reactive power flow.

3) *Efficient adjustments*

The overhead lines in the transmission levels are presently being replaced by underground cables. In the future, partial 400 kV lines and all 150/132 kV transmission lines will be constructed as underground cables [4]. A large number of shunt reactors e.g. shunts with fixed size and tap-able shunts, as shown in Fig. 1, will thus be placed to fully compensate the cables for maintaining the voltage levels. Therefore, it will be very difficult for operators to manually adjust the highly increased number of discrete reactive power control devices in a short term to obtain a satisficed voltage profile for the entire system especially with fewer or even no conventional power plants in operation.

In addition, with the commissioning of the new HVDC interconnection Skagerrak (SK) 4, the total transfer capacity of HVDC links between Denmark and Norway will reach 2400 MW. Based on the existing requirements, the maximum ramping rate is fixed at 30 MW/min per HVDC link and the maximum transfer capacities is limited to 600 MW from one hour to the next in different price zones [5]. This means that reversing the flow direction between northern Jutland and Norway from -2400 MW to +2400 MW requires 8 hours, which is becoming unacceptable for the trading mechanisms of the Nordic electricity market in the future. One of the reasons to limit the ramping rate is time-consuming manual adjustments based voltage control system.

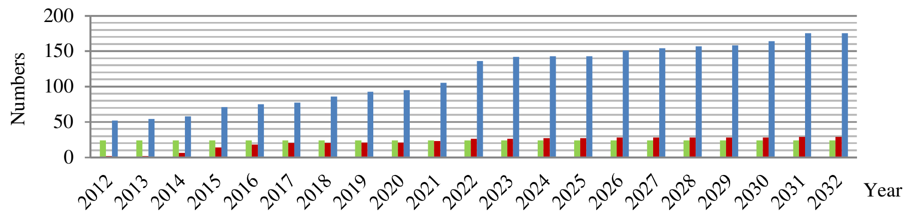

Fig. 1 Planned shunts. Blue: fixed shunt reactor; Red: tap-able shunt reactor; Green: shunt capacitor.

The present voltage control system based on manual adjustments in normal situations and preventive control in emergency situations may be insufficient in the future grid. An Automatic Voltage Control (AVC) system is therefore expected. This paper surveys some of the existing AVC systems in Section II, and then proposes the preliminary concept of an AVC system for the Danish grid in Section III. Section IV concludes the paper and proposes future studies.

II. AVC SURVEY

This section survey existing AVC systems to inspire the design of the Danish AVC system.

A. Hierarchical control

The hierarchical control is proposed in 1972 by the French company Electricité de France [6]. The general structure is shown in Fig. 2. It normally comprises of three levels that are different in terms of response time of the regulations, i.e. Primary Voltage Regulation (PVR) with several milliseconds to second response time, Secondary Voltage Regulation (SVR) with several minute response time, and Tertiary Voltage Regulation (TVR) with a quarter to an hour response time [7-9].

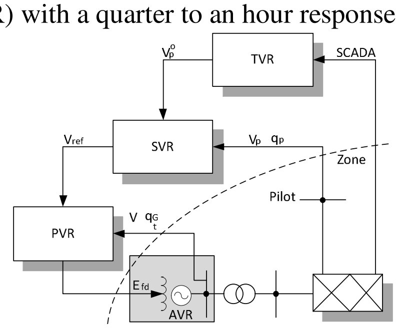

Fig. 2 The general hierarchical structure of AVC system

PVR is fully automatic and act to compensate for voltage or reactive power disturbances. In the case of the system condition changes significantly e.g. from low load to peak load condition, the reference of the AVR should be adjusted by SVR accordingly for achieving the satisfied voltage profile and maintain the reactive power reserve.

SVR is the core of the hierarchical control, it secure the voltage by dispatching the set point for PVR components. The whole system is typically decomposed for several zones where a SVR is placed in each zone [6, 9]. A pilot bus for each SVR is suggested in each zone to be monitored, which is then used by the regulators to maintain the voltage profile. Normally the pilot bus is a load bus that represents the maximum resemblance to the area voltage profile i.e. the values of voltage deviations throughout all load buses due to small disturbances are minimized [10]. For each zone that contains a pilot bus, the regulatory components are capable of providing sufficient reactive power to maintain the pilot voltage within the acceptable limits. The interactions between different zones are minimized after decomposition i.e. the zones are 'electrically far away' from each other [7]. Moreover, the pilot bus in each zone is sufficient robust against the uncertainties due to the topological or operational changes in the actual power system. Various techniques are therefore proposed for pilot bus selection and grid decomposition. The most common method is based on the electrical distance concept and clustering algorithm [10, 11]. Once the pilot bus can be sophisticated selected, it provides the possibility to control the voltage efficiently with limited information in a large scale power system. Hence the pilot bus selection plays the most important role for SVR in the hierarchical control scheme.

TVR coordinates different zones in the control of the voltages and the reactive power for the common objective, e.g. coordinate zones to minimize the overall system losses. In the real time environment, TVR dispatches the set points of the pilot bus on the basis of the actual state of the electrical system and of the optimal voltage profiles. Coordinated Secondary Voltage Control is firstly proposed in the French system to take the interactions between adjacent zones into account [12]. The method performed in TVR in [13] preserves the decentralized nature of SVR by using the reactive power tie-line flow measurements in the control function, and share the reactive power reserve when control limits are reached.

B. Centralized control

The centralized control is another scheme for a voltage control system, e.g. in Switzerland [14], there is no formal SVR and TVR in the AVC system. The centralized control coordinates the AVR of the synchronous generators and the tap positions of the transformers to maintain voltages at all nodes within the acceptable limits. In a centralized voltage control system, there is no pilot bus. The synchronous generators and the other components receive the set points from the control central at the same time. Unlike the hierarchical AVC system, the reactive power reserve among the power plants may not be shared with the equal percentage of their capacity. Without defining the pilot bus, the voltages at all buses are needed to be taken into account as constraints for the optimization model. This control scheme is suitable for a small scale system with a limited number of control components.

C. Algorithm

The Optimal Reactive Power Flow (ORPF) based AVC system requires a reliable and fast algorithm to obtain the solutions in the real time system. A variety of methods are used to solve the ORPF problem. The conventional optimization methods include linear programming [15], non-linear programming [16], gradient based techniques [17] and mixed integer programming [18]. Today, the hybrid decoupled OPF approach is wildly used in Chinese AVC systems [19]. The conventional optimization methods may trap to the local minima since the problem is inherently non-convex and highly nonlinear. In recent years, the artificial intelligent (AI) methods such as neural networks [20], genetic algorithms [21] and particle swarm optimization [22] are proposed to solve the reactive power optimization problem in the planning stage. These methods are capable of searching for the global optimized solution. However, they typically need long computational time due to many iteration loops. The real time system requires that the optimal solution in SVR should be calculated within 1-2 minutes, when AVC acquires the measurement data and calculates the optimal set points for all control components. There are still barriers in the implementations of AI solutions in a real time system.

D. Summary

As shown in Table 1, the existing AVC systems in different systems are presented. In the hierarchical system, the pilot bus in SVR is normally predefined offline [6, 9, 23 and 24] but it can also be selected in the real time system via the adaptive pilot bus selection method [11]. SVR in each region is responsible for correction of the voltage violation on the pilot bus and ensures the sufficient reactive power reserve in each region [8, 9]. The reactive power production in each region is always shared among the power plants homogeneously proportional to their capacity [9, 23 and 24]. TVR coordinates the voltage profile in the wide system and dispatch the set points to the pilot buses [9].

The synchronous generators are the backbone of this system due to their relatively large sizes of the reactive power source and the short response time on the disturbances. The shunt compensators and the taps of the transformers are primarily controlled to assist the synchronous generators in reserving their reactive power regulation capacity for transient contingency situations.

In France, the AVC control effectiveness is enhanced by CSVC. Instead of binding the pilot voltage in each region by SVR, CSVC controls several pilot voltages in a larger region and computes set points for the generators at 10-second intervals [8].

In Italy, the reliability of the AVC system is enhanced by REPORTs in each local power plant [9]. In case the plant loses the telecommunication to the SVR or TVR, the plant can regulate the local voltage at the high voltage side according to the planed set point with a certain reactive power margin. The forecast of the voltage and the limit of the reactive power are included in the Italian AVC system at TVR to minimize the overall losses [9]. The voltage set points are found offline based on the forecast snapshots. The real time system minimizes the differences between the measurements and the forecasted references.

The Swiss open-loop centralized AVC system makes Day-ahead Reactive Planning based on the Day-ahead Congestion Forecast for minimizing the cost of active power losses and the reactive power payments to generators [14]. The 24 hourly optimal voltage set points for generators and the transformers tap-positions are found day-head via ORPF.

In Spain, the 'voltage plan' provides the voltage set points at the generators, the tap positions of transformers and shunt reactors scheduling for coordination of different reactive power sources with a horizon of one year [24].

The number of switching time for the capacitors is limited in Belgian AVC system considering the reactive power reserve at generators [23].

Table 1 The existing AVC in different systems and the expected Danish AVC system

Country	Structure	Closed loop	Forecast	Objective	Controllers	Inequality constraints
France [6-8]	H	x		✓ Correction of voltage violation at pilot bus ✓ Correction of terminal voltage for generators ✓ Correction of reactive power violation for generators	✓ Generators ✓ High voltage Capacitors	✓ Voltage variation at the terminal of generators ✓ Voltage magnitude at the sensitive bus ✓ Voltage magnitude at the high-voltage side of generator ✓ Reactive power of generator
Italy [9]	H	x	x	✓ Correction of voltage violation of pilot bus including the effect of forecast set points for losses minimization ✓ Correction of reactive power violation of zones including the effect of forecast set points for losses minimization	✓ Generators ✓ Shunts ✓ Transformer ✓ FACTs	✓ Voltage limits ✓ Components limits
Belgium [23]	H			✓ Maximization of the reactive power margin on each group of synchronous generators ✓ Minimize the switching of capacitor banks ✓ Restricted inter reactive power flow to neighbor systems ✓ Voltage correction	✓ Generators ✓ Shunt capacitors ✓ Transformer	✓ Voltage limits ✓ Components limits
Spain [24]	H		x	✓ Solve congestions ✓ Correction of voltage violation primary for low-voltage problem	✓ Generators ✓ Shunt reactors ✓ Transformer	✓ Voltage limits ✓ Components limits ✓ Auxiliary services limits
Switzerland [14]	C		x	✓ Cost minimization of losses plus reactive power payments	✓ Generators ✓ Transformer	✓ Voltage limits for all nodes ✓ Voltage differences between nodes ✓ Reactive power flow on ties ✓ Components limits
China [11]	H	x		✓ Adaptive Pilot selection ✓ Losses minimization ✓ Correction of voltage violation	✓ Generators ✓ Transformer ✓ Shunts	✓ Voltage limits ✓ Components limits
British Columbia [25]	C			✓ Losses minimization ✓ Correction of voltage violation	✓ Shunts ✓ Condensers ✓ SVCs	✓ Voltage limits for the selected nodes ✓ Components limits
Denmark	*C*	*x*	*x*	✓ *Correction of voltage violation* ✓ *Cost minimization*	✓ *Shuns* ✓ *Condensers* ✓ *SVCs* ✓ *VSC-HVDC* ✓ *Transformer*	✓ *Voltages limits for all bus* ✓ *Components limits (reactive power reserve)* ✓ *Cost on regulations*

III. DANISH AVC CONCEPT

The Danish transmission system is very flexible due to its transit-dominated characteristics, the high penetration of wind power and a large number of dispersed generation units in the distribution levels. To address the challenges mentioned in Section I, a Danish AVC system is proposed.

A. Centralized AVC

The pilot bus approach utilized in existing AVC systems provides the promising results for effectively control of the overall system voltage with only limited monitoring in large power systems. However, this approach is not addressed at the early stage of the AVC system, since the Danish power system is relatively small and flexible i.e. the limited numbers of conventional power plants locate electrically close to each other; the commissioning of conventional power plants highly depends on the price in the market, which results in different pilot buses and zones in different operational conditions. Therefore the centralized control scheme in the Danish transmission grid is preferred.

B. AVC Objective

The goal of the Danish AVC system is to automatically maintain the voltage for all buses and minimize the loss at the transmission level due to reactive power flows on branches. The difficulty is to achieve the goal in conditions where only few continuous regulating components are available in all situations with high wind, and the short-circuit capacity is typically low. In contrast, large numbers of discrete controllers i.e. the taps of the power transformers, the switchable and the tap-able shunts are planned to be used for regulations. The cost of regulating these components in the AVC system, should be taken into account as the Swiss and Belgian AVC systems [14, 23], since the saved power loss due to optimally regulate the reactive power may be less than the cost of adjusting the components. The number of switching time can be limited [23]. The objective function is subjected to the constraints of the power balance, the voltage limits and the regulation limits of the components.

$$\min_{u\in(t_{tri},Q_{si},Q_{gi})}(C_z P_{loss} + \sum_{s\in NS} C_s + \sum_{k\in Nk} C_k + \sum_{i\in NG} C_{gi}\,|Q_{gi}|)$$

s.b.

$$h(x) = 0$$
$$V_{i,min} \le V_i \le V_{i,max}$$
$$u_{min} \le u \le u_{max}$$

where u is the controllers for AVC, which comprises of discrete controllers i.e. the regulating reactive power of shunts, Q_{si}, the taps of the transformers, t_{tri}, and the continuous regulation components e.g. the reactive power of the generators, Q_{gi}. P_{loss} is the system active power loss. C_z is the marginal price of zones for Danish system that is converted to price/MW instead of price/MWh. C_s and C_k are the switching cost of the shunt breakers and the taps of the transformers and the tap-able shunts per time, respectively. C_{gi} is the cost of continuous regulation components. Q_{gi} is the required amount of reactive power regulations. NS and NK are the numbers of switching for shunts and transformers taps, respectively. NG is the number of generators.

C. Prioritize the controller

The cost for these discrete components can be estimated as the total cost of the capital investment and the maintenance over the switching times. It provides AVC to prioritize the controllers according to the sensitivity respected to the objective function. As known, the cost of generators for adjusting the reactive power output is much lower than the switching cost of discrete control components. Therefore, the generators are preferred to be regulated priory to the discrete components. The reactive power reserve in the generators can be considered as constraints in the ORPF calculations.

D. Forecast

The fluctuation of the renewable energy could dominate the voltage variations in the future. In order to efficiently maintain the voltage, day-ahead and short-term forecast may be required, as the AVC systems in Italy, Swaziland and Spain [9, 14 and 24]. The real time system can thus optimize the control actions according to the forecasted solution and the real states to minimize the differences [9].

Another expectation from the forecast is to reduce the switching frequency of the discrete components. The statuses of the discrete controllers are expected to be found via the day-ahead plan considering the impact of the power plants. The correction may though be needed in real time operations. In this way, the number of switching is expected to be reduced.

E. Fallback strategy

As REPORTs in Italian system [9], a fallback strategy is expected to be implemented in case a certain substation loses the telecommunication to the control center or several stations are isolated from the main grid. Local fallback controllers can be set up. The logic can thus be made to trigger the control actions based on the sensitivity of the voltage change at the controlled bus respected to the reactive power change of the regulator, to maintain the voltage closed to the pre-fault value. Another application of fallback controllers is to help AVC to correct the voltage violations in the normal operations. For examples, in case the voltage violates the operational limits but not triggers the relays, AVC may need several minutes to correct the voltage violation since AVC dispatches the set points every 2-3 minutes. The fallback controllers can be activated to correct the violations priory to AVC.

F. Integrate RPC

There are 18 stations equipped with RPCs which controls the shunts and the taps of the transformers to regulate the reactive power locally. The time constant of the RPCs are much shorter than the AVC system. In order to avoid frequent switching of the discrete components by either RPC or AVC, the impact of RPCs on the AVC system should be evaluated to avoid conflicting control effects between RPCs and AVC. A preliminary solution is to integrate RPCs as normative regulators in the AVC system. The AVC system dispatches set points to RPCs after ORPF is carried out.

G. Integrate distribution grid

The dispersed units in the distribution grids may participate to the voltage control in the transmission level e.g. the 'cell controller pilot project' demonstrates that cell controllers at a 150 kV station can coordinate the dispersed units in the distribution level to supply reactive power regulations for the transmission grid as virtual power plants [26]. The effect from active distribution grids should be further investigated for different system topologies and operational conditions. This mixed centralized and decentralized AVC system is considered for a later stage of the Danish AVC solution.

IV. Conclusion

This survey paper presents some of the existing AVC systems, which inspires the concept design of a Danish AVC system to address the future challenges of voltage control. As shown in Fig. 3, the Danish AVC is based on a centralized control scheme i.e. all the buses are monitored where the voltage magnitudes are maintained continually. The loss minimization including switching cost is the objectives of the AVC system. Day ahead and short-term forecast is to be implemented to reduce the working load of the real time system, as well as to minimize the numbers of switching times of the discrete components. The fallback controllers are to be installed in selected substations to enhance the system reliability and the robustness. RPCs will be integrated to AVC system as normative regulation devices. Distributed generation units can be organized as virtual power plants and participate in voltage control at transmission level. Systematical evaluation of the effect of voltage control from different aspects should be conducted in future work. Energinet.dk as Danish TSO will implement the first stage of the AVC system by 2016.

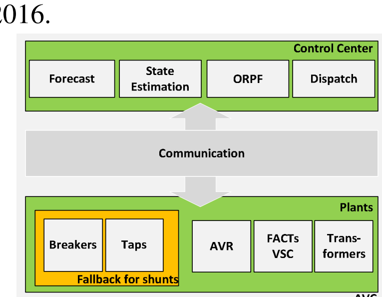

Fig. 3 The Danish AVC system. The control center dispatches the set points to the regulators in the plants via telecommunication networks. The set points are found based on the ORPF algorithm. The fallback controls mainly regulate the shunts locally are activated in case the telecommunications is lost or the voltage violates the defined limits immediate after the AVC dispatches the set points.

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