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Flexible Automatic Generation Control System for Embedded HVDC Links

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Abstract— Frequency quality will be maintained as ancillary service instead of utilities, and different qualities in one system may be requested depends on the framework of service. This paper proposes a flexible *Automatic Generation Control (AGC)* system for embedded HVDC links in order to provide frequency sensitive response and control power interchange.

Index Terms-- Automatic generation control, frequency controller, frequency stability, power system, protection scheme, wind turbine generator.

I. INTRODUCTION

Future energy systems networks will be completely different to the power systems on nowadays [1], [2]. High and low power converters will be massively deployed in several areas on the electric network [3], [4], [3]: (i) renewable energy from highly variable generators connected over high power converters, (ii) several technologies for energy storage with very different time constants, some of them using power converters as an interface to the grid, and (iii) Pan-European transmission network facilitating the massive integration of large-scale renewable energy sources and the balancing and transportation of electricity based on underwater *multi-terminal high voltage direct current* transmission. The developments of stronger interconnector and massive integration of offshore wind power in remote location are steadily increasing the demand for more robust, efficient, and reliable grid integration solutions. Multi-terminal *Voltage source converter (VSC)*-based HVDC (MTDC) technology has the potential to increase transmission capacity, system reliability, and electricity market opportunities.

The developments of stronger interconnector and massive integration of offshore wind power in remote location are steadily increasing the demand for more robust, efficient, and reliable grid integration solutions. Multi-terminal *Voltage*

source converter (VSC)-based HVDC (MTDC) technology has the potential to increase transmission capacity, system reliability, and electricity market opportunities.

The integration of VSC-HVDC links into transmission systems has the potential to afford a powerful new tool for controlling both over and under frequency conditions. The high degree of controllability inherent to the active power flow on an HVDC link allows rapid changes to the power flow to be used to counter active power imbalances [5].

Primary frequency control in HVDC has been a hot topic in recent times. Several publications has developed and tested controllers to enable *inertial response* on HVDC systems [6-9]. HVDC for primary frequency control has been considered in several publications [10], [11], and the coordinated primary frequency control among non-synchronous systems connected by a multi-terminal high-voltage direct current grid is studied in [12]. Also, the problem of providing frequency control services, including inertia emulation and primary frequency control, from offshore wind farms connected through a MTDC network has been studied in [13]. However, *secondary* and *tertiary frequency control* considering HVDC or MTDC systems has deserved a very low attention in recent publications.

This paper proposes a flexible *Automatic Generation Control (AGC)* system for embedded HVDC link in order to provide frequency sensitive response and control power interchange.

II. PROPOSED AGC INCLUDING EMBEDDED HVDC LINK

The structure of the proposed AGC of the *interconnected power system* or area is shown in Fig. 1. There are four control levels of the active power and frequency control. The upper system control level is presented by the AGC of the power system. The input signals are the system frequency measurement f_{meas} in the power, the scheduled power on the interface (P_{tie}) and line interchanges (AC lines: $P_{flow,k}$, and DC lines: $P_{DC,ij}$).

Fig. 1. The structure of the automatic generation control.

Based on *tie-line interchanges*, the net interchange power ($P_{net,ref}$) is calculated as:

$$P_{net,ref} = \sum_{k=1}^{N_{branches}} P_{flow,k} + P_{DC,ij} \quad (1)$$

In the AGC of the power system (at the system control level) the system frequency deviation (Δf) and the changes on the net interchange power (ΔP_{net}) deviations are defined as:

$$\Delta f = f_{sys} - f_{ref} \quad (2)$$

$$\Delta P_{net} = P_{net} - P_{net,ref} \quad (3)$$

where: f_{ref} is a frequency set point value (typically, the rated or nominal frequency), $P_{net,ref}$ is a net interchange power set point value. The area control error (ACE) is calculated as:

$$ACE = -\Delta P_{net} + K_{bias} \Delta f \quad (4)$$

where: K_{bias} is the frequency bias.

In the event of the internal power imbalance of the power system, ACE defines the power to be compensated by the regulating power plants and the HVDC link in order to enforce frequency stabilization between the areas [14]. In the case of the external frequency disturbance due to the different signs of frequency and net interchange power deviations ACE value tends to zero that provides the selectivity of the AGC operation depending on location of the disturbance [14], [15].

The unscheduled active power setting P_{AGC} formed by the proportional-integral (PI) controller on basis of is calculated as follows:

$$P_{AGC} = K_P ACE + K_I \int_{t_1}^{t_2} ACE dt \quad (5)$$

where: K_P is the proportional gain of the PI controller; K_I is the integral gain of the PI controller; t_1 , t_2 are the integration limits.

As shown in Fig. 1, the control i -th AGC control signal P_{AGCi} , is transmitted to each regulating power plant, defined according to the participation factor α_i of individual power plant in the secondary frequency control:

$$P_{AGC,i} = \alpha_i P_{AGC} \quad i = 1, 2, \dots, n \quad (6)$$

At the power plant control level the signal P_{PCi} formed by the power plant PI controller is calculated as:

$$P_{PCi} = K_P^{PC} \left(K_f \Delta f + \Delta P_{agci} - \sum_{j=1}^m \Delta P_{Tj} \right) + K_I^{PC} \int_{t_1}^{t_2} \left(K_f \Delta f + \Delta P_{agci} - \sum_{j=1}^m \Delta P_{Tj} \right) dt \quad i = 1, 2, \dots, n$$

where: K_P^{PC} is the proportional gain of the power plant PI controller; K_I^{PC} is the integral gain of the power plant PI controller; K_f is the coefficient of frequency correction; and $\sum \Delta P_{Tj}$ is the sum of the turbine power change of the generating units participating in the secondary frequency control.

The distribution of the control signal P_{PCi} at the i -power plant control level is performed in accordance with the participation factors β_{ij} of the generating units of i -power plant in the secondary frequency control (see Fig. 2):

$$\Delta P_{ij} = \beta_{ij} P_{PCi} \quad i = 1, 2, \dots, n \text{ and } j = 1, 2, \dots, m \quad (7)$$

where: n is the number of the regulating power plants; m is the number of the generating units of the i -power plant; ΔP_{ij} is the control signal from the power plant controller. The control signal $\Delta P_{ij,ref}$ is distributed in such a way that:

$$P_{PCi} = \sum_{j=1}^m \Delta P_{ij} \quad i = 1, 2, \dots, n$$

and

$$P_{agc} = \sum_{i=1}^n P_{agci} = \sum_{i=1}^n \sum_{j=1}^m \Delta P_{ij} \quad i = 1, 2, \dots, n$$

The calculated control signal ΔP_{ij} from the power controller is transmitted to the turbine governor of the generating unit (aggregate control level) via the speed changer motor (see Fig. 2). Further, according to the reference control signal ΔP_{ij} , the turbine governor generates a signal of the turbine power change ΔP_{tij} . Thus, the power changing of the generating units restores the normal frequency and scheduled net interchange power.

Frequency quality will be maintained as ancillary service instead of utilities, and different qualities in one system may be requested depends on the framework of service.

The AGC is a significant control process that operates constantly to balance the generation and load in power systems at a minimum cost. In this paper, the proposed AGC include a control system to provide signals to embedded HVDC links in order to provide frequency sensitive response and control power interchange.

III. SIMULATION AND RESULTS

The IEEE 14 Bus Test Case represents a portion of the American Electric Power System (in the Midwestern USA) as of February, 1962. The original IEEE 14-bus system (as presented on [16], [17]) has been slightly modified, the system has three Power Plants and a boundary has been defined to establish 2 operational areas (Area 1 and Area 2 in Fig. 2). Not depicted in Fig. 2, but included in the system

model, are generator controllers (IEEE Type 1 speed-governing model), such as the automatic voltage regulators (SEXS, *Simplified Excitation System*).

The interface between areas is defined by three overhead transmission lines (OHL 1-5, 1-2/1 and 1-2/2), as consequence the AGC is developed to monitor and control the net power interchange on them.

Fig. 2. Modified IEEE 14-bus test system.
The proposed AGC model has been developed using *DigSILENT Simulation Language (DSL)*.

Fig. 3. General frame of the AGC model.

Fig. 5. General frame of the Proposed AGC+HVDC control model.
Figs. 6 to 7 illustrate comparative results using classical AGC (CASEI: NO AGC, CASE II: Classic AGC) and the proposed method.

Fig. 6. Results using classical AGC.

Fig. 7. Results using Proposed AGC.

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