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Provision of Ancillary Services for Balance Management in Autonomous Networks

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Abstract--**The main hypothesis underlying the work presented in this paper is that the future power system will rely on large amounts of distributed generation (DG) with large percentage of renewable energy based sources. Consequently, this system will be characterised by significantly increased uncertainties on generation side and therefore, its behavior in time will be more difficult to control. This paper discusses the current methods for balance management. Furthermore it considers the limitations and presents a novel approach for balance management in a future situation.**

I. INTRODUCTION

THE European electricity grid is one of the largest power systems in the world. Due to economies of scale it has always been advantageous to increase its size. There is currently a large grid with an approximate yearly consumption of 2400 TWh and a maximum load of 390 GW [1] which supplies electricity to more than 400 million customers. Most of the European countries are synchronously connected to this grid. This means that the frequency in all of these interconnected countries is identical (in steady-state). The vast majority of the electricity in this grid is produced with large synchronous generators. These generators are rotating electric machines that have large inertia due to their mass. This inertia helps to keep the grid's frequency constant. Due to environmental, economical and geopolitical reasons [2] there will be a shift in the production of electricity. More and more distributed generation will be integrated in the system, some of which have significantly different characteristics when compared to the existing large synchronous generators [3].

There should always be a balance between the supply and the demand of electricity. Any deviation results in a change of the frequency of 50Hz. A set of ancillary services is in use to control the frequency, and therefore the power balance of the grid. The rules to which these services should comply are given by the Union for the Co-ordination of Transmission of Electricity (UCTE) in [4].

The remainder of the paper is organised as follows. In section II we present and discuss the control schemes used for power balance management in today's European power system. In section III we argue about the limitations of these control schemes for future power system, and discuss the possible reasons that hamper the straightforward continuation of today's practice. Following these considerations, in section IV we present a novel approach for the settlement and provision of ancillary services for balance management. Conclusions are summarised in Section V.

II. BALANCE MANAGEMENT

In order to elucidate the problems and possible solutions concerning reliable power balancing in future power systems, it is important to understand how these problems are solved today. The main goal of this section therefore is to give a short overview of the current power balance management in the European grid.

Electricity is a good which can hardly be stored economically on a large scale. Therefore there must always be a balance between production and consumption. Since most electricity generators are rotating machines, their rotational speed and thus also the frequency will decrease if more power is extracted than inserted. Vice versa, the frequency will increase if more power is inserted than extracted. Therefore it can be concluded that the deviation from the nominal frequency is an indication for an imbalance in the system. Since the grids of many European countries are synchronously interconnected, the UCTE has set up rules for stabilising the balance between supply and demand. Different control mechanisms have been designed and are incorporated as ancillary services in the grid.

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The different control mechanisms are defined as primary control, secondary control, tertiary control and time control. In this paper, tertiary control and time control will not be discussed further since their application is outside the scope of this paper. The different controllers are subsequent and act on different timescales. Figure 1 shows the hierarchy of the different controllers to control the grid's frequency. Each member of the UCTE can decide whether or not to apply incentives to motivate market players to participate in each of these controllers. In the next sections these different controllers will be explained in some more detail.

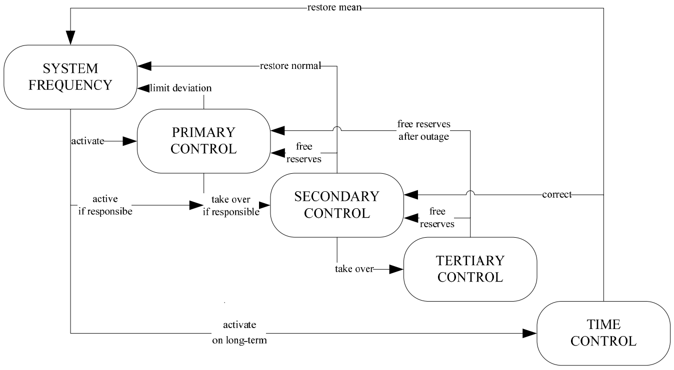

Fig. 1: Hierarchy of the different controllers to control the frequency in the grid [4]. Self-regulation is incorporated in the system frequency block.

A. Primary control

Whenever there is any imbalance between supply and demand, the frequency starts changing. Primary control acts within seconds after a distortion, with a goal to stabilise the system and to prevent any further frequency deviation. The primary control of generators is designed to increase the production if the frequency is lower than the nominal frequency and to decrease production if the frequency is above its nominal value. The rate at which a generator participates in this control is called the droop of a generator which is defined as follows (1):

$$S_G = \frac{-\Delta f / f_n}{\Delta P_G / P_{Gn}}, \qquad (1)$$

where S_G is the droop of the generator, Δf is the frequency deviation, f_n is the nominal frequency (i.e. 50Hz), ΔP_G is the generator output and ΔP_{Gn} is the nominal generator output.

The aim of the primary control is to stop the deviation of the frequency and to set the frequency to a so-called quasi-steady-state value. In general, this value is different from its nominal value. The obliged participation of each country in the primary control action is based on the yearly production of electricity in that country [4]. The individual contributions of each country are shown in figure 2. On the vertical axis in this figure the contribution is given in MW/Hz. This is the power which each country will produce extra if the frequency drops with 1 Hz. Each country is free to select any method or market system for accumulating this required amount of primary control action, i.e. either by commercial means or a mandatory obligation [5].

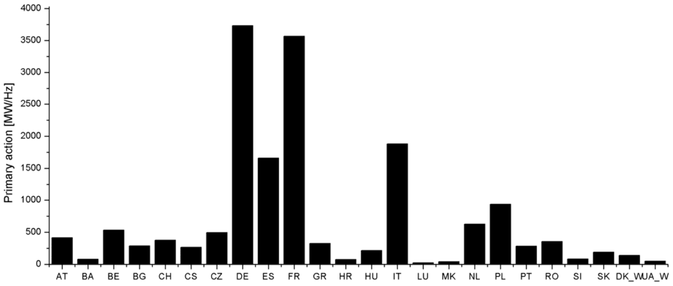

Fig. 2: Primary action of UCTE-members [1], [4].

B. Secondary control

After primary control action, secondary control is activated to restore the frequency from its quasi-steady-state to its nominal value. The secondary controller acts slower than primary control and it is only active in the control zone where the imbalance between supply and demand is caused [4]. For that purpose, the so-called area control error (ACE) is defined as follows (2):

$$ACE = P_{meas} - P_{prog} + K \cdot \Delta f, \qquad (2)$$

where P_{meas} is the actual cross-border exchange, P_{prog} is the programmed cross-border exchange, K is a constant (in MW/Hz) which is defined for each country and Δf is the frequency deviation [4]. Each control zone is required to activate its secondary control in order to drive its ACE to zero. Note that in Europe, the borders of the control zones in most cases coincide with the borders of a country.

The calculation which country has caused the imbalance is a function of both frequency and the difference between planned and actual import and export. Since each country is responsible for settling its own imbalance, it should reserve a certain amount of production capacity for secondary control. This amount is based on the maximum load of each country. Figure 3 displays the minimum recommended amount of reserved capacity for automatic secondary control for each UCTE-member.

Although there are strict limitations to the restoration path of the frequency set by the UCTE, control zones are free to select any method or market system for accumulating the required amount of secondary control action. In this way, causing imbalance is penalised more in one country than another.

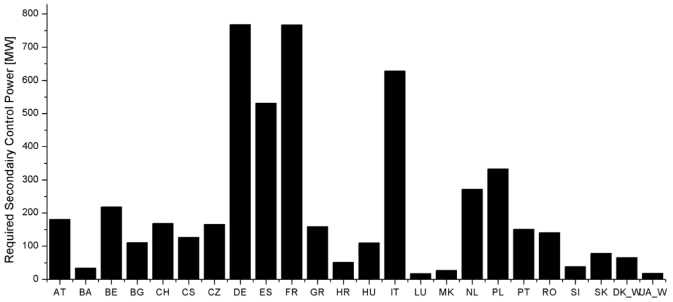

Fig. 3: Minimum recommended capacity for automatic secondary control for UCTE-members [1], [4].

C. *Self-regulation*

One of the advantageous properties of the electricity grid is the self-regulation of the load. A large share of the electric load consists of rotating machines of which the consumption depends on the frequency. Therefore a decreasing frequency will result in a decrease of power consumption. Estimations for the value of this self-regulation vary from 1% to 2% per Hertz [4]. This self-regulation has a positive effect on the stability of the frequency in the grid, where it contributes in the same fashion as the primary control action.

D. *Effects of the individual control mechanisms*

Figure 4 illustrates the trajectory of the network frequency deviation with the different control loops active, as indicated in the legend [4]-[8]. Note that primary control is crucial for the stability of the system, while the secondary control is required to drive the steady-state frequency deviation to zero.

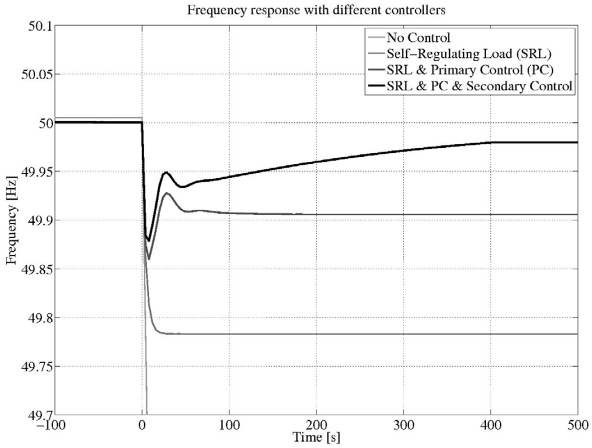

Fig. 4: Frequency response with several controllers.

III. POWER BALANCE MANAGEMENT IN FUTURE POWER SYSTEMS

One of the crucial changes which are taking place in today's power system is the encouragement of the large-scale integration of DG, many of which are based on intermittent renewable sources like wind and sun. This integration of DG is already taking place for some time now and, for renewable sources, many countries have posed high targets over ten years horizons [2]. Non-dependence on fossil fuels of many DG technologies, together with environmental issues are the main driving forces towards those targets.

A. *Dispersed generation as provider of high services*

Note that one of the main reasons for the reliability of traditional power systems is due to the controllable synchronous generators. With synchronous generators, the initial step in the power balancing is pretty much given for free. The synchronous generator is a significant buffer of kinetic energy and reduces the need for active control in covering the continuously occurring imbalances.

Distributed generation units include micro-turbines, fuel cells, wind turbines, photovoltaic arrays, combined heat and power plants, small hydro-power plants, biomass power plants, geothermal power plants, tidal power plants, etc. Across the set of different DG technologies, there is a huge variety of possible time responses to the power imbalances. DG units are typically not based on synchronous generators. Some units operate asynchronously, coupled to the grid via AC-AC power electric converters. Others are non-rotating, inertia-less sources, such as photovoltaic units and fuel cells. With an absence of the rotating inertia, such sources introduce very different characteristic to the system, and their ability to respond to the fast occurring imbalances will likewise be very different from that of the traditional units.

This response of the different units is shown in figure 5 [9], [10], [11]. Conventional generators are capable of following the increasing load. Wind turbines have some inertia which enables them to produce the required amount of power instantaneously but immediately afterwards their power production decreases due to the deceleration of the turbine. Fuel cells react slowly. We can imagine that with a combination of fuel cells and wind turbines the response of the conventional generator can be imitated. In order to do that however, online knowledge about the availability of the different types of DG and their inertia would be necessary. Ancillary services for balance management have to be adjusted according to this availability.

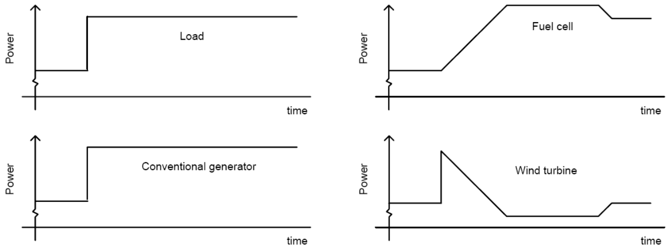

Fig. 5: Increase in power for load and different generators [9].

B. *Time-varying requirements for ancillary services*

It is important to note that today's power systems are characterised by a highly repetitive pattern of aggregated demand. From one working day to the other, the variations in the aggregated demand profiles are only a couple of percent. This explains why the current minimum requirements for ancillary services could have been defined as constant over long time horizons, i.e. see figure 3 for the case of secondary control.

It is expected however that a large portion of the distributed generation units will be based on intermittent renewable sources like wind and sun [2], [12]. The consequence will be a large increase of the uncertainties in any future system state prediction. Large and relatively fast fluctuations in production are likely to become normal operating conditions, standing in contrast to today's operating conditions which are characterised by highly repetitive and therefore highly predictable, daily patterns. The current reservation of ancillary services, based on failing production facilities or maximum load requirements in a control zone will not suffice. For higher degrees of DG ancillary services for balance management should be available, based on active DG production facilities. Since DG production is often based on renewable recourses which are difficult to predict, this means that the required amount of control power will change continuously. As an example, we can think of two days with completely different wind production. Consequently the production by other generators will be different on these days and therefore the requirements for balancing services also change. The variability of wind power is illustrated in figure 6 where the different lines display the wind power in the Irish grid on several days within one month. From the figure can be concluded that wind power in the power system can differ significantly among days and even the fluctuation of wind power within one single day can be large [13]. This variability of DG needs to be taken into account when reserving ancillary services for balance management.

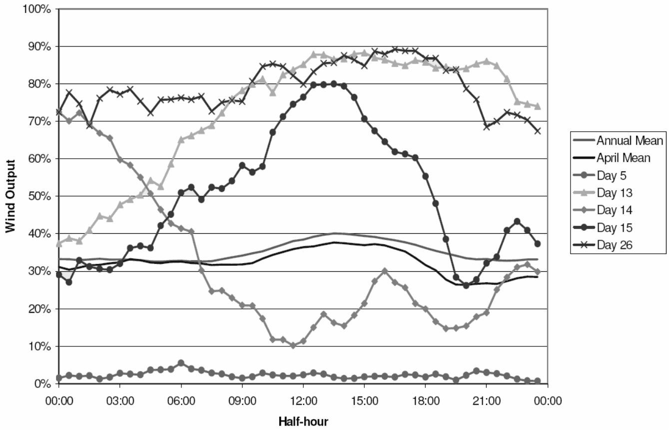

Fig. 6: The output of wind power in the Irish power system for several days within one month [13].

C. Demand side management

As stated before, the demand contributes passively as control power in the current power system because of the self-regulation. However, the demand has a great potential to participate in balance management. Currently, consumers have no incentive to cooperate in balance management and their demand is price-inelastic [14]. By introducing incentives [15] and the technical means to implement demand side management the load can be adjusted whenever required. Based on the incentives, consumers could select several reliability levels for different applications. For balance management, the different reliability levels correspond with the amount of control power which can be made available within a specific time.

IV. AUTONOMOUS NETWORKS

By increasing the share of DG, the complexity of the grid increases due to an increase of the number of generators. In [14] it has been shown that autonomous networks (ANs) can be used to balance supply and demand in such a complex system.

A. Concept

In this concept, ANs are considered to be building blocks in which consumers and producers are aggregated based on their geographical location or another form of cooperation. Towards the outside world, ANs behave as single entities with a certain production or consumption. The aggregation into ANs takes place on several levels. Since producers and consumers are grouped in a small area, there is aggregation on a physical level. However, in the concept van ANs, parties are also integrated on an economical level. On this economical level, ANs are able to trade energy and ancillary services in double sided markets while behaving as single units. Figure 7 shows the structure of ANs.

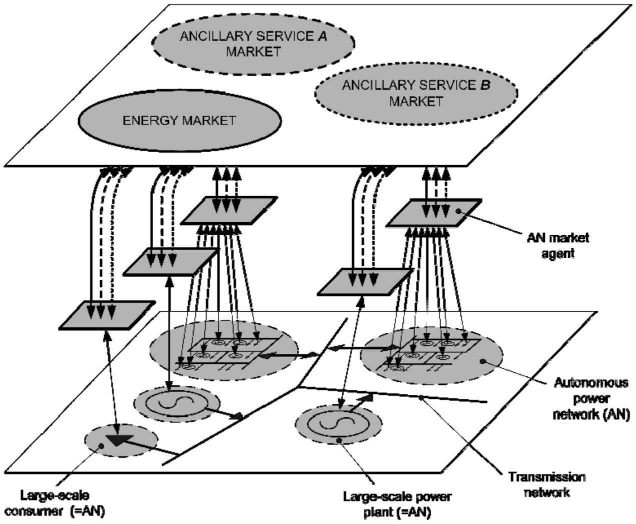

Fig. 7: Autonomous power networks [14]

The figure displays the different levels on which the aggregation takes place. In the concept of ANs, the production and consumption within each AN depends on the local prices in the network. Therefore, congestion in the network will cause the prices for different services to differ from each other.

We can state that ANs are already present in today's power systems in the form of control areas of the corresponding transmission system operators. They are an intermediate, coordination based layer of the operational structure of the European power system. Loosely speaking, we can see the concept of ANs as further refinements, or as decomposition, of the already present structure with some additions such as the possibility to introduce trade of ancillary services. Introduction of large amounts of distributed generation (DG) is taking place in virtually all geographical areas and not only on the transmission network level, but also close to the loads in the medium and low voltage (distribution) networks.

B. Balance management

As discussed before, supply and demand of electricity should always be in balance. Ancillary services for balance management are used to restore any imbalance in the grid. The two most used controllers for this are primary and secondary control. Since primary control is only based on the frequency it can also be implemented in DG. Secondary control however requires data on the planned and real exchange amongst control zones. Currently, secondary control is implemented in single sided markets where market players are asked, based on their availability, by the TSO to supply secondary control power.

The benefit of the ANs concept is the possible introduction of the double-sided competitive markets for ancillary services. Such markets are characterised with a large amount of players on both supply and demand side. The competition and the responsibility of delivering the traded commodities, create the incentive for reduction of uncertainties in the system. To benefit from the advantages of aggregation of consumers ANs should have a certain size. This aggregation reduces the unpredictability of the load of consumers and consumers are not required to all have control power available.

The capability of ANs to deliver balancing power depends on the content of the AN. Therefore in the concept of ANs, each AN decides whether or not to be available for the production and trade of ancillary services for balance management.

Being part of ANs, consumers are also capable of delivering control power. Either by generating electricity with DG or by switching off part of their load, they can contribute to the balance of supply and demand. A technical infrastructure with smart meters and an incentive for consumers to change their demand from price-inelastic to price-elastic would enable consumer's active role in ANs.

V. CONCLUSION

In this paper the control mechanisms were discussed which are currently in use to guarantee the balance between supply and demand of electricity in the grid. For primary and secondary control, the individual contribution to frequency control was briefly discussed. In future power systems, DG is expected to play an important role. The introduction of DG however, also hampers the continuation of the use of the existing balancing systems. By changing the architecture of the systems for the provision of ancillary services DG can contribute to balance management. Intelligent structures such as autonomous networks can accommodate control power in a decentralised way. In double sided markets the individual entities (ANs) can trade balancing power based on their available production capacity and individual requirements. The selection of the ANs for the provision of balancing power can be based on price levels.

VI. ACKNOWLEDGMENT

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VIII. BIOGRAPHIES

Jasper Frunt was born in 's-Hertogenbosch in 1981. He received his B. degree in electrical engineering in 2003 from the University of Professional Education in 's-Hertogenbosch. In 2006 he received his M.Sc. degree in sustainable energy technology from Eindhoven University of Technology. For his graduation projects he worked with Kema N.V. and Tennet TSO bv (Dutch Transmission System Operator) respectively. Currently he is a PhD in the EOS (Energy Research Subsidy) project 'Regelduurzaam' for Eindhoven University of Technology. His research focusses on current and future deployment, legislation and organisation of control power for balance management.

Andrej Jokic was born in 1976 in Zagreb, Croatia. He received his Dipl.Ing. degree (cum laude) in Mechanical Engineering from the Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb in 2001. In 2007 he received his PhD at the Control Systems group of the Department of Electrical Engineering, Eindhoven University of Technology. His research interests are: large-scale interconnected systems control and optimization.

Wil L. Kling received his M.Sc. degree in electrical engineering from the Technical University of Eindhoven in 1978. Since 1993 he has been a (part-time) professor in the Department of Electrical Engineering at Delft University of Technology, in the field of Power Systems Engineering. In addition, he is with the Transmission Operations department of TenneT (the Dutch Transmission System Operator). Since 2000, he has also been a part-time professor at the Technical University of Eindhoven. His area of interest is related to planning and operations of power systems. Prof. Kling is involved in scientific organizations such as CIGRE and the IEEE. As Netherlands' representative, he is a member of CIGRE Study Committee C6 Distribution Systems and Dispersed Generation, and the Administrative Council of CIGRE.

Johanna M. A. Myrzik was born in Darmstadt, Germany in 1966. She received her MSc. in Electrical Engineering from the Darmstadt University of Technology, Germany in 1992. From 1993 to 1995 she worked as a researcher at the Institute for Solar Energy Supply Technology (ISET e.V.) in Kassel, Germany. In 1995 Johanna joined to the Kassel University, where she finished her PhD thesis in the field of solar inverter topologies in 2000. Since 2000, Johanna is with the Eindhoven University of Technology, the Netherlands. In 2002, Johanna became an assistant professor in the field of distributed generation. Her fields of interests are: power electronics, renewable energy, distributed generation, electrical power supply.

Paul van den Bosch was born in Rotterdam in the Netherlands. He obtained his Master's Degree in Electrical Engineering and completed his PhD thesis on "Short term optimization of thermal power systems" at Delft University of Technology, where he was appointed full professor in Control Engineering in 1988. In 1993 he was appointed to the Measurement and Control Chair in the Departement Electrical Engineering at the Eindhoven University of Technology and in 2003, also to the Department of Biomedical Engineering. He has authored about 150 scientific publications and supervised about 250 Master's and 30 PhD students. His main research interests deal with modelling and control issues, real industrial products and processes, with considerable experience in electromechanical systems, embedded systems such as the interface between computer science and control, automotive applications and biomedical processes.