Power System Control with Renewable Sources, Storages and Power Electronic Converters

Prof. Dr.-Ing Harald Weber, Preethi Baskar, Nayeemuddin Ahmed
Electrical Energy Supply (EEV)
Institute for Electrical Power Engineering (IEE)
University of Rostock
Rostock, Germany
harald.weber@uni-rostock.de

Abstract—**In the future, the electrical power supply networks will be transformed from conventional power plant structures with inertia to a complete inertia independent system with storages for different generation speed together with power electronic converters. In this paper, a method is proposed to control the electrical power distribution by these new power plants. All the control principles necessary involving spinning reserve, primary control and secondary control depending on frequency are substituted by a comprehensive angle control of the nodal voltages in the transmission and distribution network. It is observed that whenever the power requirement of the loads increase, the slacks generate more power with the slack power station closest to the point of increasing consumption automatically producing the most power. However, this can lead to a dilemma because one slack cannot have unlimited generation capability. Hence, the paper also depicts the system response when one slack reaches its maximum power generation limit.**

Keywords—converters and storage, PQ node, PV node, re-dispatch reduction, slack, voltage angle control

I. INTRODUCTION

Frequency control reserves are an essential ancillary service in any electric power system, guaranteeing that generation and demand of active power are balanced at all times [1]. Thus, whenever there is an increase in the active power demand, the system employs its speed or frequency related control to counter this discrepancy. The control mechanism enables the system to initially satisfy this additional demand from the instantaneously available spinning reserve power (inertia from flywheels) and then the primary reserve power (from centrifugal force governor) [2].

However, this situation is quite complex in context of today's electrical networks, for example the ENTSO-E (European Network of Transmission System Operators for Electricity), since they span across many international borders [3]. Such vast networks contain hundreds of synchronous generators and a diversified range of loads with numerous interconnections. Due to adopting frequency control, a stepwise increase in the load demand in one section within such an integrated network leads to the use of spinning reserve power followed by the generation of primary control reserve power throughout the grid. This means that every generator in the integrated grid must adjust its power output proportionally to satisfy the change in load demand.

Another issue with power plants today is that most steam engines and steam turbines use fossil fuels. Due to the limited reserves of such resources and also the high carbon dioxide emission resulting from their usage, a switch towards using renewable energies in the future is inevitable [4]. In Germany, this would mean using solar and wind power. However, since these sources are fluctuating, the energy generated in this way has to be stored on a larger scale in the foreseeable future.

Thus, to resolve these issues a new type of power plant is described in this paper which will be able to integrate and store energy from renewable sources [5]. Moreover, these power plants will not possess any flywheels or rotating masses eliminating the need for frequency based control. The central idea is to have these futuristic storage power plants function as high output converters which can be connected to solar and wind sources as well as High Voltage Direct Current (HVDC) cables.

Such converters can also function with present day conventional power plants which contains rotating masses. In this case, the converters have to adapt to the turbine flywheel masses and their respective frequency. This can be done by synthetically generating rotating inertia and primary reserve power. To achieve this, the converters have to measure the momentary active power at the connecting node so that they can properly feed their angle-oriented regulating power into the grid. This way, the new converters also function as power stations and can therefore be integrated into the system.

However, in the future, the number of conventional power plants will be reduced or they will disappear completely due to the unavailability of fossil fuels. They are expected to be replaced by an increasing number of the proposed high power output converters without flywheel masses functioning as storage power plants. In that case, the adaptation of modern power converters to rotating flywheels will be obsolete. Furthermore, due to the absence of rotating parts altogether, such power plants can be controlled by a new method of grid control knows as the Nodal Voltage Angle control. The advantages of such a control method as well as having storage power plants as part of the electrical grid are described in the next sections of the paper.

978-1-5090-5948-5/18/$31.00 ©2018 IEEE

II. THE NEW "CONVENTIONAL" OR STORAGE POWER STATION

The fundamental principles of electric power supply and power system control are valid universally. For every type of generation, transmission, distribution and consumption the following conditions must be met:

1) Large scale, highly dispersed power supply requires a three-phase network [6].
2) Sudden load changes have to be fed instantaneously by spinning reserve from inertia or equivalent.
3) The storages of this spinning reserve power soon have to be released and recharged, in the seconds range, by the primary control power. To that end, storages for primary control power are necessary [7].
4) Primary control power, in the minute range, has to be replaced by secondary control power. Then the primary control storage has to be recharged as well.
5) Following this, the scheduled power output of the plant has to be adjusted to replenish all used storages to their nominal value.
6) If the power supply is entirely based on renewable energies, an additional requirement has to be met. Certain amounts of the "harvested" energy have to be stored for forecast errors and cold periods (without wind and sun).

As of today, these tasks are being performed by conventional power stations. This consists of a chain of components which is made of converters/adapters and storages operating at different speeds. Fig. 1b shows an example of a coal power station's component chain. Its mode of operation shall be demonstrated with an example of a stepwise electric power requirement at the generator terminal:

1) ***Conversion/adaptation:*** The stepwise electric power requirement is instantaneously converted by the generator at an unchanged speed into a stepwise increase of the air gap torque and therefore of the mechanical output power.
2) ***Storage:*** The rotating masses consist of a turbine-generator-exciter system. It instantaneously converts part of its kinetic energy and supplies this as mechanical output power. As a result, the speed declines. The speed here corresponds to the amount of stored kinetic energy.
3) ***Conversion/adaptation:*** The primary controller accesses the live steam storage (drum boilers or forced bypass boilers) via the turbine valve, increasing the steam flow in the range of a few seconds. The turbine torque rises and recharges the inertia storage.
4) ***Storage:*** Due to the increased steam flow there is a decrease in steam pressure. At this point the steam pressure marks the amount of energy present in the steam storage.
5) ***Conversion/adaptation:*** To adjust the steam pressure, the fuel governor increases firing. More carbon and oxygen are converted into carbon dioxide, and the evaporator generates more steam. The increased

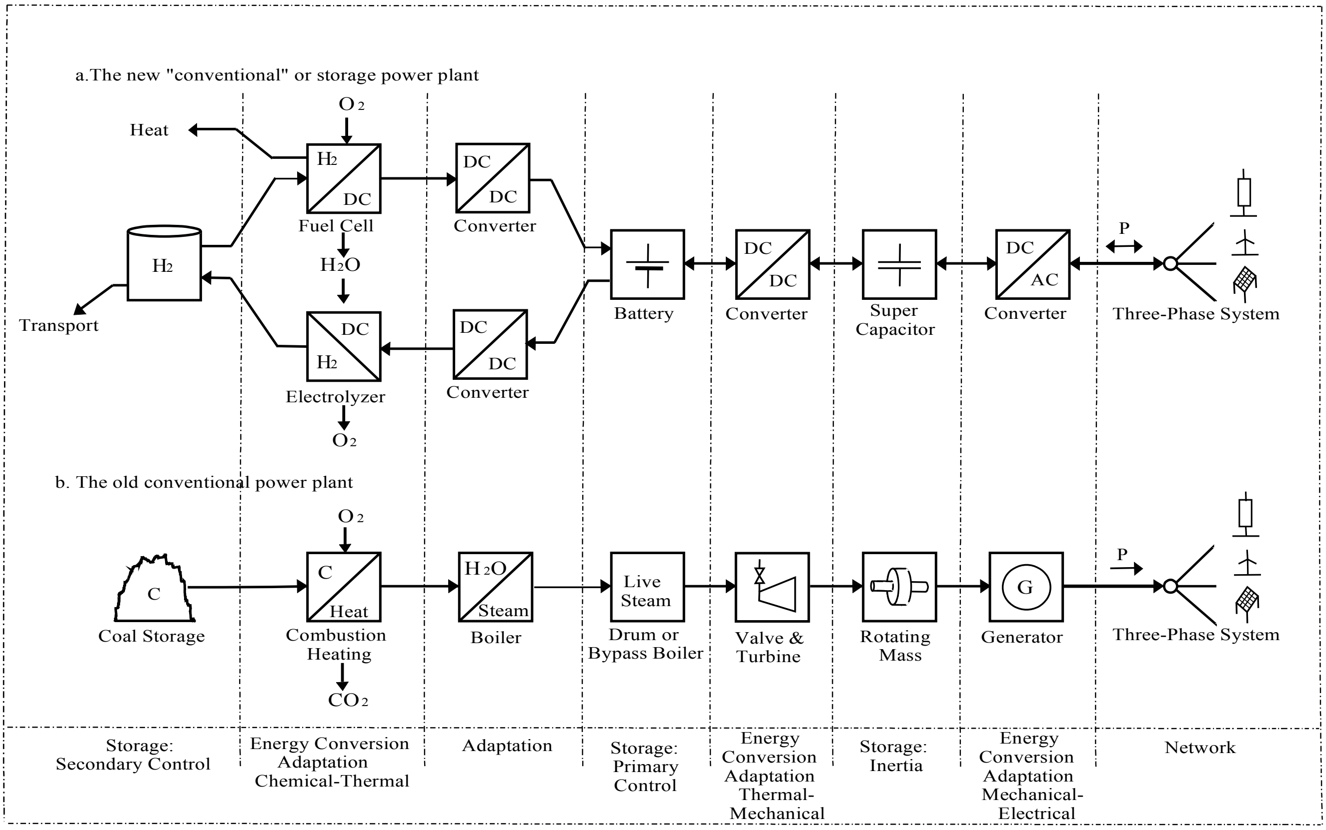

Fig. 1. The new storage power plant *(a)* & the existing fossil fuel plant *(b)*

steam flow restores the reservoir pressure in the boiler.

6) **Storage:** The fuel governor accesses the coal store, in the minute range, and increases the mass flow of fuel. As the amount of coal decreases, so does the amount of stored energy. It cannot be recharged by the power station itself.

Due to the increasing presence of renewable energies like wind and solar power, conventional power stations have to drastically reduce their output at certain times in order to make room for the renewables. To that end, the minimum power supplied has to be lowered and the control rate has to be raised. Every power station using fossil fuels today has to fulfil these requirements [8,9].

A new kind of "conventional" power station is required in order to be able to perform the above-mentioned tasks regarding power supply and grid control in a world relying completely on renewable energies. Such power stations would not only supply power during cold periods without wind and sun, but would also be able to store excess energy. At the same time, these power stations will have to operate during a transitional period with a flywheel mass-based power supply from power stations existing today. If the power supply is completely converter-based they can be used in either grid-forming or grid-supporting mode given a constant grid frequency, signifying the transition to angle control.

Fig. 1a shows the component chain of a new type of flywheel mass-free power station, which can work in grid-forming mode. Its mode of operation will also be demonstrated with an example of a stepwise electric power requirement at the DC/AC converter:

1) ***Conversion/adaptation:*** The stepwise electric power requirement at the converter with a constant nodal voltage angle (grid-forming) leads to an instantaneous increase of three-phase AC current and therefore also an instantaneous increase of direct current on the DC side of the adjacent converter.
2) ***Storage:*** The super capacitor instantaneously accesses its stored electrical energy and supplies this as output power. A capacitor is chosen for this purpose because it can immediately supply large magnitudes of power. As a result, the voltage of the super capacitor decreases, which marks the amount of stored energy. These properties are analogous to that of the spinning reserve in conventional power stations.
3) ***Conversion/adaptation:*** The downstream DC/DC converter's governor (between the battery and the super capacitor in Fig. 1a) has to keep the capacitor voltage constant. To this end, it accesses the battery increasing the battery output power in the second range. As a result, the capacitor charging current increases and this recharges its voltage storage. These properties match that of the primary control of conventional power stations.
4) ***Storage:*** Due to the increase in battery output power there is a decrease in battery voltage resulting in a decline in the amount of stored energy as well.
5) ***Conversion/adaptation:*** The fuel cell's control unit increases the fuel cell's activity in order to charge the battery and replenish its voltage. At the same time, hydrogen and oxygen are converted into water (H_2O) while the DC/DC converter between the fuel cell and the battery adjusts the required voltages enabling the charging current to recharge the battery storage.
6) ***Storage:*** The fuel cell's control unit accesses the hydrogen storage in the minute range and increases the fuel's input mass flux. The amount of hydrogen in the storage decreases, marking the amount of stored energy. It may be refilled by the plant autonomously via the electrolyzer.

During steady state operation, the required power is effectively transferred from the hydrogen storage to the thee phase network. The battery or the capacitor storages are not used to satisfy the requirement of the network during this situation. These storages only act, when the consumption or production in the network changes suddenly, in order to instantaneously respond and provide the necessary control actions autonomously.

Contrary to the old type of power station, which only is able to reduce its output to a certain minimum, this new type of power station can actually reverse its output. In case of a production surplus from renewable resources there is a shock-free transition from fuel cell operation to electrolyzer operation. The corresponding converters adjust the voltage of each component, while the electrolyzer produces hydrogen of the required pressure. This new type of "conventional" power station may therefore be called a Storage Power Station.

III. FREQUENCY CONTROLLED OPERATION OF A STORAGE POWER PLANT

To be able to function effectively in the existing frequency-controlled energy supply system, the storage power station has to be able to react to the supply frequency and its derivative with the supply of spinning reserve and primary control power. To that end, the storage power station operates in a modified grid-forming mode, which is comprised of two components. The following sections explain the working principle utilizing equations where all values are in per unit except for the angles-

A. Spinning Reserve Power

The storage power station produces a target power output of p_{S0} as shown by equation (1) and dictates a nodal voltage $\underline{u}_s$ as exhibited by equation (2).

$$p_{S0}=p_{S0,scheduled}+p_{S0,secondary}+p_{S0,primary} \tag{1}$$

$$\underline{u}_S=u_S\cdot e^{j\varphi_U} \tag{2}$$

Thereby, every requirement regarding spinning reserve is automatically fulfilled at the first moment. The momentarily provided output power p_S is being measured. The synthetic equation of motion is used to simulate a speed change for changes in the momentarily provided output power.

$$\Delta\dot{\omega}_S = -\frac{1}{T_S}\cdot(p_S - p_{S0}) \tag{3}$$

In combination with equation (4) or (5) this leads to an integral adjustment of voltage angle φ_U by the DC/AC converter, resulting in equation (6).

$$\Delta\dot{\varphi}_U = \Omega_0 \int \Delta\dot{\omega}_S \cdot dt \tag{4}$$

$$\Delta\varphi_U = \Omega_0 \int \Delta\omega_S \cdot dt \quad \text{and} \quad \Omega_0 = 2\cdot\pi\cdot f_0 \tag{5}$$

$$(p_S - p_{S0}) = 0 \tag{6}$$

As a result, the spinning reserve power with the time constant T_S is extracted from the super capacitor.

B. Primary Control

Equations (3), (4), (5) and (6) in combination operate like a PLL circuit which measures the change in the angular supply frequency $\Delta\omega_S$. With a given power station droop σ_S, the power station output p_{S0} can be rearranged according to

$$p_{S0} = p_{S0,\,scheduled} + p_{S0,\,primary} = p_{S0,\,scheduled} - \frac{1}{\sigma_S}\cdot\Delta\omega_S \tag{7}$$

As a result, the DC/AC converter can fulfil the task of primary control at the required control rate. While doing so, the battery gradually recharges the super capacitor. Decrease in battery voltage causes the fuel cell to use the hydrogen storage. Primary control power is then reloaded and the battery is recharged by the hydrogen storage in the long run.

If the storage power station participates in secondary control, the DC/AC converter's secondary control power, $p_{S0,secondary}$, will be raised until the control area's Area Control Error (ACE) has become zero and the supply frequency is back at its set point of 50 Hz. If a supply solely delivering primary control power is required, then T_S is set to 0. Therefore the control rule becomes:

$$\Delta\omega_S = -\sigma_S\cdot(p_S - p_{S0}) \tag{8}$$

Such a characteristic of primary control power has for instance been implemented in the 5 MW battery storage in "Schwerin, Germany" as a so-called "Droop Control".

IV. ANGLE REGULATED OPERATION OF A STORAGE POWER PLANT

When the energy supply system will mainly rely on storage power stations, "Watt's speed control" will no longer be required. The three-phase supply can be operated at a constant frequency, for instance, f_0 at 50 Hz. The tasks of grid control like spinning reserve and primary control power can be fulfilled using the nodal voltage angle at the storage power station's connection point. The grid itself with its admittances and voltage angles operates as a coordinating unit. It provides all the required information using its given load flow. Storage power stations can operate either in grid-forming mode, as so-called slack power stations (voltage source), or in grid-supporting mode, as so-called PV power stations (current or power source). These features are present in the current conventional power stations with a certain time delay from either an integral acting angle control (slack behaviour) or an integral acting active power control (PV behaviour). To that end, all power stations have to know the present voltage angle at their connection point as well as the 50 Hz angle standard of their control area via an accurate radio-controlled quartz clock. This clock can be synchronized via the time signal transmitter DCF77 of the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig, Germany once each day.

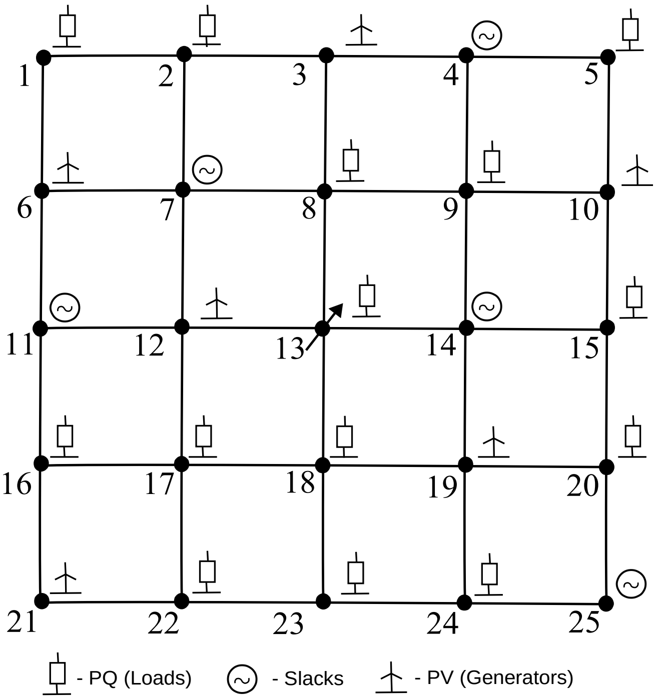

Fig. 2. 25 node example network (Slack, PV & PQ nodes)

The mode of operation of this new type of grid control is best explained with an example. Fig. 2 shows a 110 kV grid with 25 nodes. The admittances between the nodes have the same magnitude and are purely reactive. The line length between any two nodes is assumed to be 50 km. Eleven power stations, of which five are slack storage power stations (generator symbol) and six are PV power stations (windmill symbol) along with 14 PQ consumers (load symbol) are connected to the nodes. Each consumer consumes 10MW of active power. Initially, a simple load flow calculation is done in such a way that all eleven power stations equally satisfy the grid's consumption of $\Sigma P_C = 14 \text{ x } 10 \text{ MW} = 140 \text{ MW}$ with each of them supplying $140/11 \text{ MW} = 12.72 \text{ MW}$ of active power. Node 25 is the slack node for this initial load flow calculation. The reactive power output of each generator is also adjusted so each generator supplies approximately the same amount. All load flow calculations are based on current iteration and are programmed in Octave 4.2.

Fig. 3, 4, and 5 show the voltage phasor of the load flow calculations respectively, for slack storage power stations, PV power stations, and PQ consumers. As shown in the diagrams, the PQ consumer's voltage phasors follow the surrounding voltage phasors of slack and PV power stations, ensuring the load flow from the generators to the consumers. For the sake of clarity, the imaginary axis is shown in a heavily overstretched manner in this depiction. Otherwise the individual angles would not have been clearly recognized.

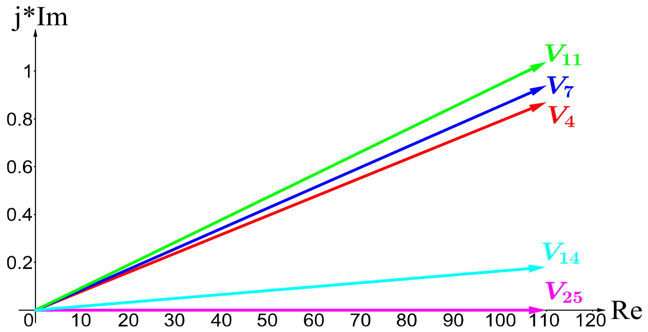

Fig. 3. Voltage phasors of slack generators (at start of load flow)

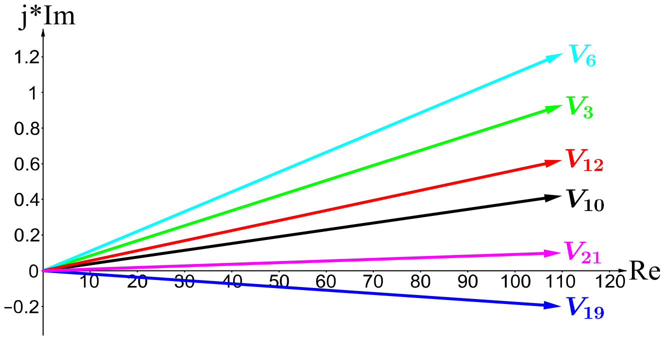

Fig. 4. Voltage phasors of PV generators (at start of load flow)

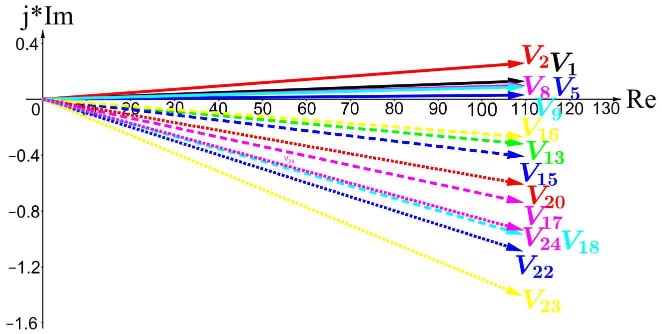

Fig. 5. Voltage phasors of PQ loads (at start of load flow)

A new case of investigation is then added in which the consumption at node 13 is increased from 10 MW to 110 MW in increments of 10 MW. For this load flow calculation all nodes with slack storage power stations are treated as slack nodes, and their voltages are taken from the initial load flow calculation with the single slack node (Node 25). The only difference in this load flow calculation in comparison to the initial one is that, here all the five rows and five columns corresponding to the slack nodes are removed from the original admittance matrix to form the reduced admittance matrix. While calculating the respective load flows, it is observed that, the angles at all the PV generator and the PQ consumer nodes change, but not those belonging to the five slack storage power stations. Therefore, the grid-forming converters of slack storage power stations are able to keep their voltages constant, both magnitude and angle, matching the properties of a slack node (constant voltage).

Fig. 6 shows the power increase of the consumer at the central node 13 and the corresponding reaction of the constant voltage slack storage power stations. The depiction shows how each of the slack storage power stations supply the additional required power according to their electrical proximity to the consumer. Thus, the slack storage power station at the neighbouring node 14 bears the brunt of the required power output (44 MW), followed by the power station at node 7 with 23.3 MW. After these, there is the slack storage power station at node 11 (17.4 MW) and finally the ones at nodes 4 and 25 at approximately equal distances from node 13 contributing 7.8 MW and 7.4MW respectively. This behaviour is exactly analogous to the combined effect of spinning reserve and primary control. This type of primary control is load flow-oriented, since the neighbouring storage power stations have a greater load to bear than the remote ones. As a result, in the event of a fault the load flow mainly emerges at the fault location while remote storage power stations contribute little in terms of power supply.

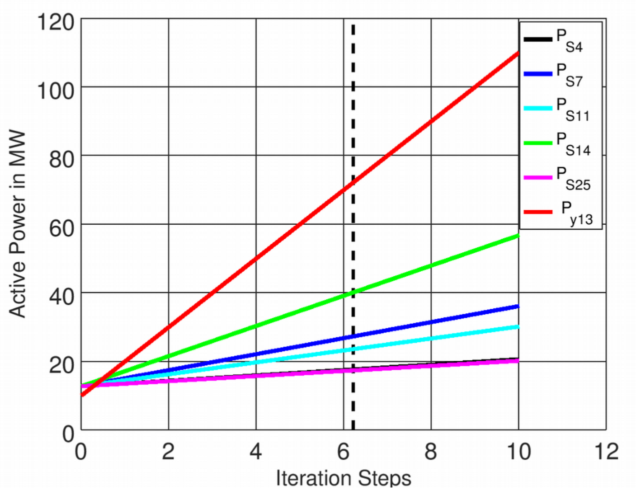

Fig. 6. Active power of slack nodes and node 13 (changing load)

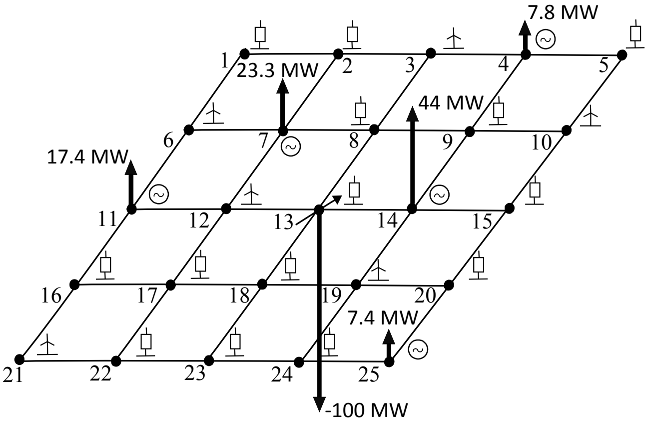

Fig. 7. Increase in power consumption in node 13 and the resulting increases in the generation of every slack power plant

Fig. 7 shows the maximum power increases of the consumer and slack storage power stations, clearly depicted as bars. Consumption is shown as a negative value, and generation is shown as positive values. The depiction clarifies how the electrical proximity to a consumer at node 13 influences the power generation of the slack nodes. For an angle-oriented primary control, power stations close to the fault location, supply more active power than the power stations further away. This satisfies the principle of generating greater power close to the consumer.

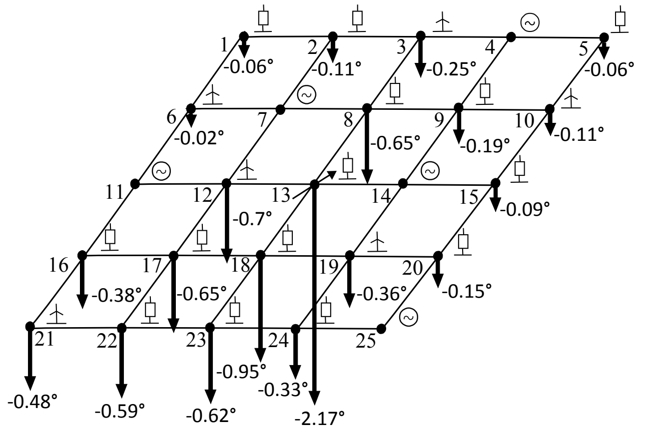

Fig. 8. Increase in power consumption in node 13 and the resulting angle changes in PV Generators and PQ consumers

Fig. 8 exhibits the angle torsion of certain nodes in the investigated grid. All angular changes of the non-slack nodes (PV generators and PQ consumers) from their initial operating point are depicted. The voltage angle of the load in node 13 has a maximum decrease of –2.17° owing to the large increase in power consumption. The resulting angle torsions in the rest of the grid due to this power increase are required by the slack power stations to provide the necessary additional power. The voltage angles of the slack power stations remain unchanged at the initial values from the first load flow calculation (see Fig. 3).

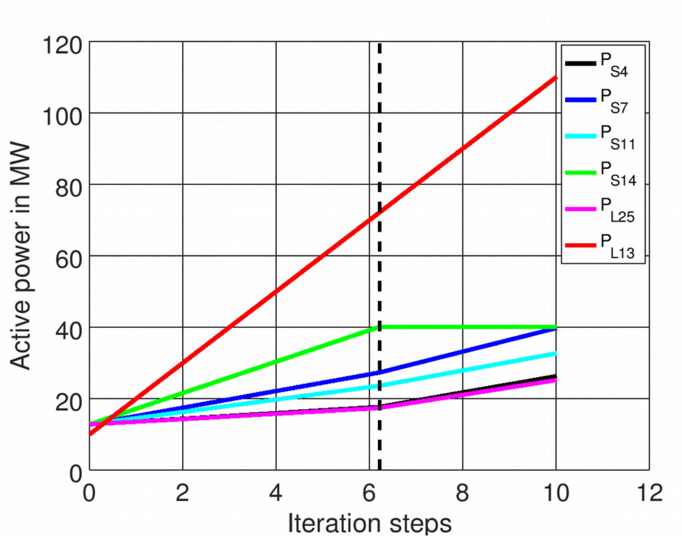

Fig. 9. Active power of slack nodes with power limitation in node 14

In the next example, it is assumed that after the 6th step increase in load, the slack generator at node 14 comes to its power limit at 40 MW. Therefore, this slack power plant now becomes a PV-Power Plant keeping its active power constant and releasing its voltage phasor i.e. allowing its nodal voltage angle to change.

As can be seen in Fig. 9, the remaining four slack power plants still operate in their current mode and increase their power output with a higher slope. As a result, these four storage power plants are now able to fulfill the total power requirement of the load at node 13.

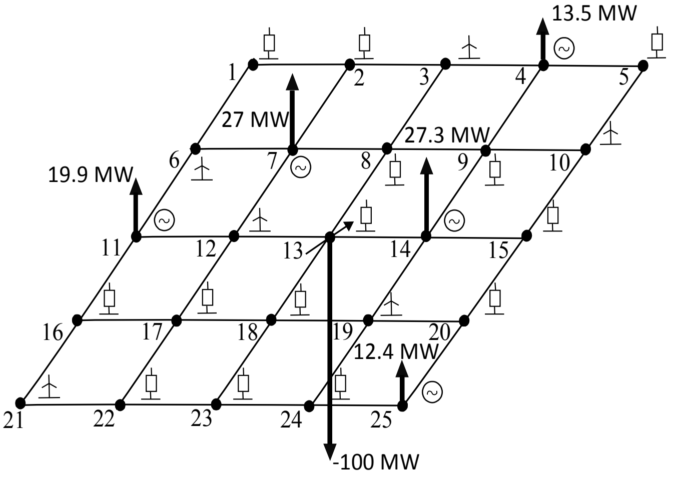

Fig. 10. Increase in power consumption in node 13 and the resulting increase in generation of the slacks with power limitation in node 14

In Fig. 10, it is depicted that the additional power supplied by the plant at node 14 is now only 27.3 MW compared to 44 MW in the previous case. However, the plant at the node 7 now produces 27 MW, which is higher than its previous production of 23.3 MW. Thus, after the limitation, the duty of maximum power production is automatically shifted to the next nearest power plant to meet the increasing load demand.

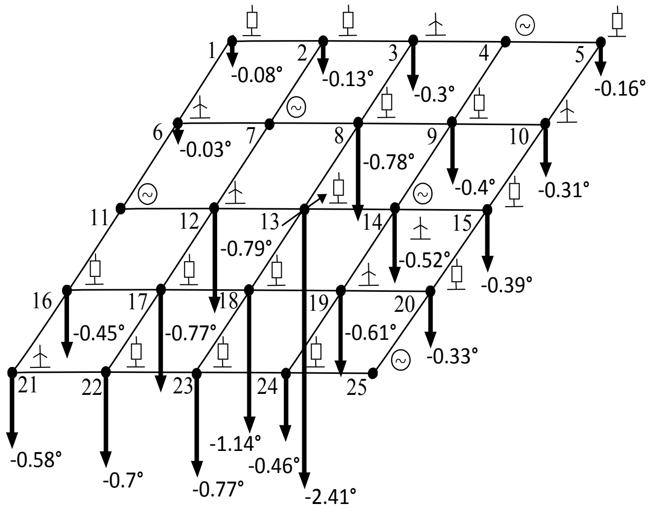

Fig. 11. Increase in power consumption in node 13 and the resulting angle changes in PV Generators and PQ consumers with power limitation in node 14

In Fig. 11, the voltage angles can be seen for the new scenario. At node 14, an angle deviation of -0.52° occurs now because of the power limitation of the slack power plant. As a result, this slack now behaves like a PV power plant and due to fewer number of slacks in the network, the angle deviations now have higher values.

SUMMARY

The flywheel mass-free storage power stations together with the modern high-performance grid control converter technology can function properly in both frequency and angle controlled networks. Within frequency controlled grids, the new power stations can operate like conventional ones, performing all tasks of ancillary services like spinning reserve, primary control, secondary control, and scheduled production. In addition, they will be able to store energy from renewable sources, making re-dispatch actions redundant.

In the future, involving angle-controlled networks, without a physical flywheel mass, these power stations can operate like slack storage power stations, making it possible to keep the grid frequency constant. This requires an exact measurement of the nodal voltage angles and an angle standard. By this method, it is also possible to automatically reduce unintended load flows in the network.

When one slack power plant reaches its maximum active power production limit, the task of additional generation can be shifted automatically to the neighboring stations. This way all possible future cases of application are covered, alleviating the process of further expansion and integration of renewable energy resources into the electrical network. However, additional comprehensive research will be required to estimate the total losses of this novel system and hence complete a quantitative comparative study with conventional power plants.

ACKNOWLEDGMENT

We are truly grateful for the contribution of James Watt and Thomas Newcomen for today's industrial advancements through the invention of the Steam Engine. In addition, we would like to thank the University of Rostock for providing us with the resources to conduct this research.

REFERENCES

[1] T. Borsche, A. Ulbig, and G. Andersson (2014). A new frequency control reserve framework based on energy-constrained units. *2014 Power Systems Computation Conference*. Doi:10.1109/pscc.2014.7038111.

[2] A. V. Meier (2006). *Electric power systems: a conceptual introduction*. Hoboken, NJ: IEEE Press.

[3] Q. Zhou and J. Bialek (2005). Approximate Model of European Interconnected System as a Benchmark System to Study Effects of Cross-Border Trades. *IEEE Transactions on Power Systems,20*(3), 1663-1663. doi:10.1109/tpwrs.2005.854741.

[4] S. Norrga and M. Hesamzadeh, "INTERGRID - Enabling a sustainable energy system by large-scale intercontinental power transmission," *2013 IEEE Power & Energy Society General Meeting*, 2013.

[5] A. Nasiri, "Integrating energy storage with renewable energy systems," *2008 34th Annual Conference of IEEE Industrial Electronics*, 2008.

[6] Holst, P. Kertscher, H. Weber: Netzintegration der Regenerativer Energien in M-V, VDI-Fachtagung Energieland 2020- die zukünftige Energieversorgung in Mecklenburg-Vorpommern, [Grid Integration of Renewable Energies in M-V, VDI Symposium Energy Land 2020 – the future energy supply in Mecklenburg-Vorpommern], 02.09.2009, Rostock.

[7] S. Alali, T. Haase, I. Nassar, and H. Weber, "Impact of Increasing Wind Power Generation on the North-South Inter-Area Oscillation Mode in the European ENTSO-E System," *IFAC Proceedings Volumes*, vol. 47, no. 3, pp. 7653–7658, 2014.

[8] C. Ziems, H. Weber: Auswirkungen zunehmender Windenergieeinspeisung auf den Kraftwerksbetrieb in Deutschland [Impact of Increasing Wind Energy Feed-In on Power Plant Operation in Germany], VGB PowerTech, Ausgabe 6/2009.

[9] S. Meinke, C. Ziems, E. Hassel, J. Nocke, H. Weber: Thermodynamische Simulation eines Steinkohleblocks unter Einbezug der Regelungstechnik mit Modelica [Thermodynamic Simulation of a Coal Block with the Involvement of Control Technology with MODELICA], 42. Kraftwerkstechnisches Kolloquium, 12.-13. Oktober 2010 Dresden.