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Power Re-Dispatch Reduction with Nodal Voltage Angle Control in Electrical Energy Supply Systems

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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. Such systems will include storages for different generation speed together with power electronic converters. In this paper, a novel 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 slack generators satisfy this rising demand with the power stations closest to the point of increasing consumption automatically producing the most power. This drastically reduces the heavy load flow and the need for general power re-dispatch measures. Reducing power re-dispatch would not only save millions of Euros on an annual basis but also lead to the formation of a more secure electrical network.

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

1. 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 many interconnections. Due to adopting frequency control, a stepwise increase in the load demand in one section 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 functions 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 contain 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.

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. In that case, the adaptation of modern power converters to rotating flywheels will be obsolete and such power plants can be controlled by a new method of grid control knows as the Nodal Voltage Angle control. The advantages of using 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.

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2. 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).

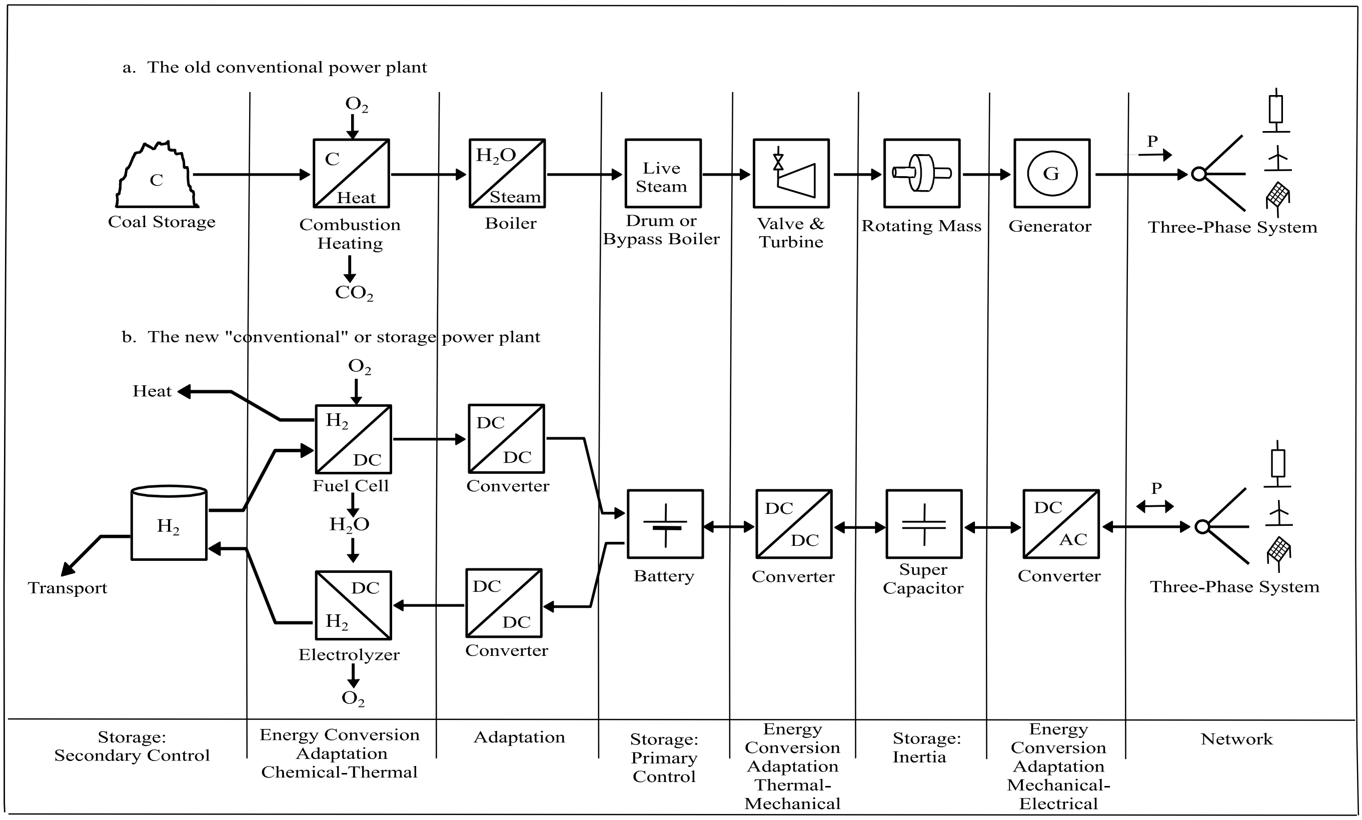

Fig. 1. Comparison between the existing fossil fuel based power plant (a) and the new storage power plant (b)

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. 1a 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 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 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. This cannot be recharged by the power station.

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 which is the basis for power stations existing today. If the power supply is completely converter-based, it can be used in either grid-forming or grid-supporting mode given a constant grid frequency, signifying the transition from frequency to angle control.

Fig. 1b 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. 1b) 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 three 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 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.

3. 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.

3.1 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).

$$p_{S0} = p_{S0,scheduled} + p_{S0,secondary} + p_{S0,primary} \qquad (1)$$

$$\underline{u}_S = u_S \, e^{j\phi_u} \qquad (2)$$

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.

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

In combination with equation (5) or (6) this leads to an integral adjustment of voltage angle φ_U by the DC/AC converter, resulting in equation (7).

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

$$= \Omega_0 \int \Delta\dot{\omega}_S \cdot dt \tag{5}$$

$$\Delta\varphi_U = \Omega_0 \int \Delta\omega_S \cdot dt \qquad \& \qquad \Omega_0 = 2 \cdot \pi \cdot f_0 \tag{6}$$

$$p_S - p_{S0} = 0 \tag{7}$$

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

3.2 Primary Control Power

Equations (3), (5), (6) and (7) 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

$$p_{S0} = p_{S0,scheduled} + p_{S0,primary} = p_{S0,scheduled} - \frac{1}{\sigma_S}\Delta\omega_S \tag{8}$$

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:

$$\Delta\omega_S = -\sigma_S.(p_S - p_{S0}) \tag{9}$$

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".

4. NODAL VOLTAGE 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, f_0, for instance 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 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.

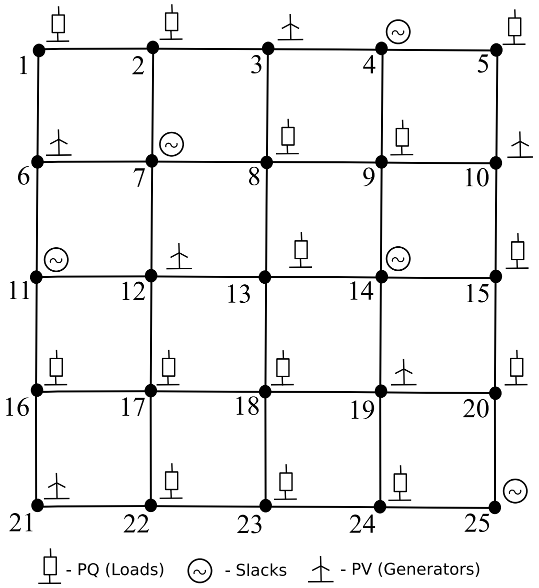

Fig. 2. Example network with 25 nodes

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, 0.3 Ω/km. The line length between any two nodes is assumed to be 50 km. There are a total of 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) in the exhibited grid. Every node is connected either to a load, PV generator or a slack generator. Each load consumes 10 MW of active power. Initially, a load flow calculation is done in such a way so that all eleven power stations equally satisfy the grid's consumption of $\Sigma P_C = 14 \times 10$ MW = 140 MW with each station supplying 140/11 MW = 12.72 MW of active power. Node 25 is the slack node for this initial load flow calculation. All load flow calculations are based on current iteration and are programmed in the software Octave 4.2.

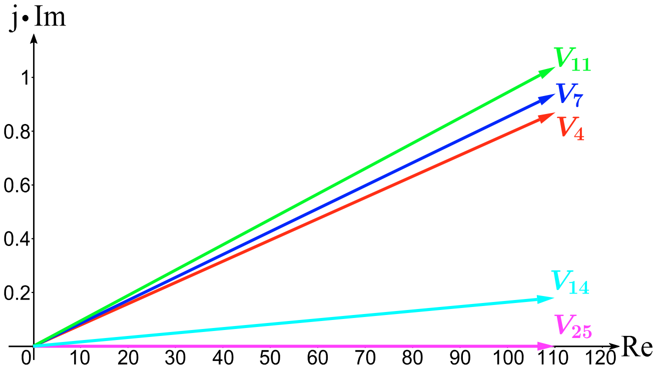

Fig. 3. Voltage phasors of slacks (start of load flow)

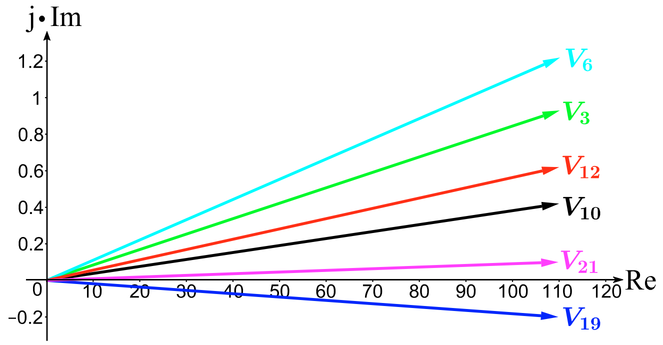

Fig. 4. Voltage phasors of PV generators (start of load flow)

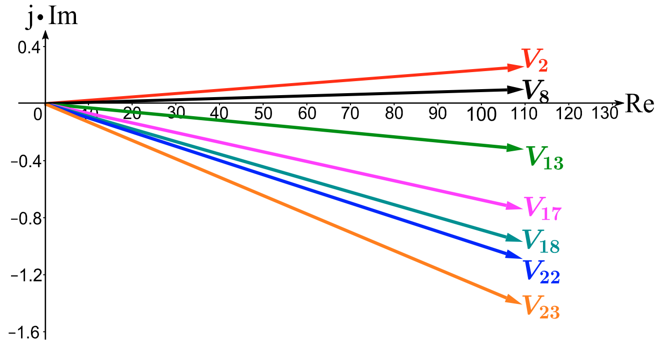

Fig. 5. Voltage phasors of some PQ loads (start of load flow)

Fig. 3, 4, and 5 show the voltage phasors of the load flow calculations respectively, for slack storage power stations, PV power stations, and some 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.

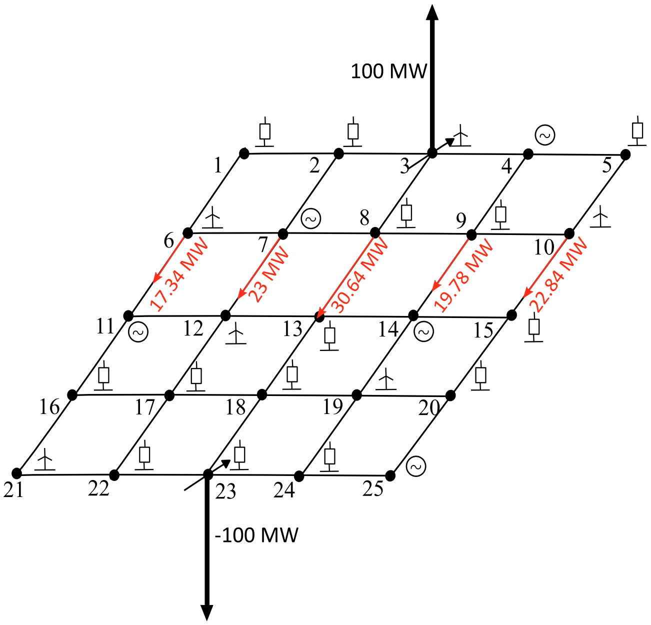

Fig. 6. Power flow with frequency control *(not to scale)*

The next example demonstrates how the slack storage power stations are also able to reduce undesirable load flows in the case of high wind power generation in one area and consumption of this power in another distant area. For exhibiting this in the network of Fig. 2, the power generation is increased by 100 MW at PV node 3 & power consumption is increased by the same magnitude at PQ node 23.

In the first case, it is assumed that the network is governed by frequency control. Since the additional consumption and production balance each other, the frequency remains unchanged and the primary controller does not act. All eleven power stations continue to produce the same active power as before. Hence, the additional produced power of 100 MW is transported completely to the consumer at node 23 generating a heavy load flow as seen in Fig. 6. Nowadays, this undesired heavy load flow has to be reduced by re-dispatch measures, which is expensive in general.

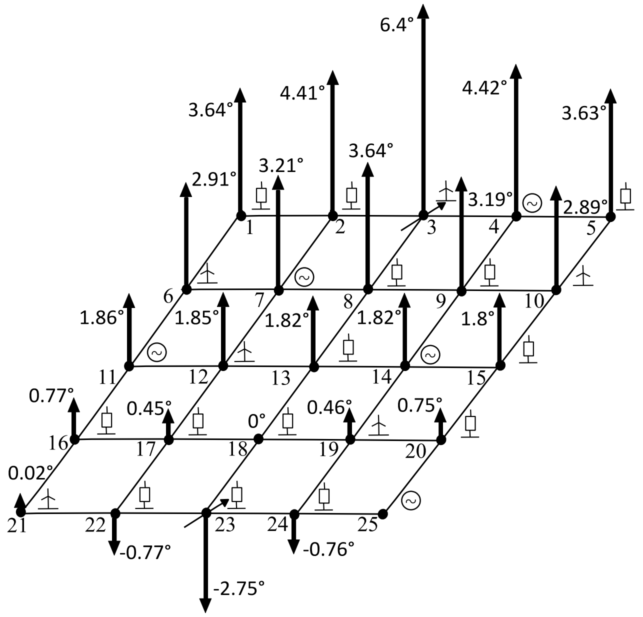

Fig. 7. Change of nodal voltage angles with frequency control

In Fig. 7, the changes in the angles of the nodal voltages are shown with respect to the slack node 25. The other slack storage power plants at the nodes 4, 7, 11 and 14 also allow their voltage angles to be changed, functioning as normal PV power plants instead of slack storage power plants in frequency controlled operation. As can be easily seen, the grid is drilled heavily (signified by the large magnitude of the angle changes) resulting in the large load flow of 100 MW from the “North” to the “South”.

In the next example shown in Fig. 8, effect of the same power changes on the network is observed under nodal voltage angle controlled operation. In this case, all the five slack storage power stations are active. As can be seen, the slacks in the “north” consume while the slacks in the “south” produce active power automatically to reduce the power flow through the transmission lines reducing the need for re-dispatch measures. As a result, the network can now be kept in a much safer and secure status.

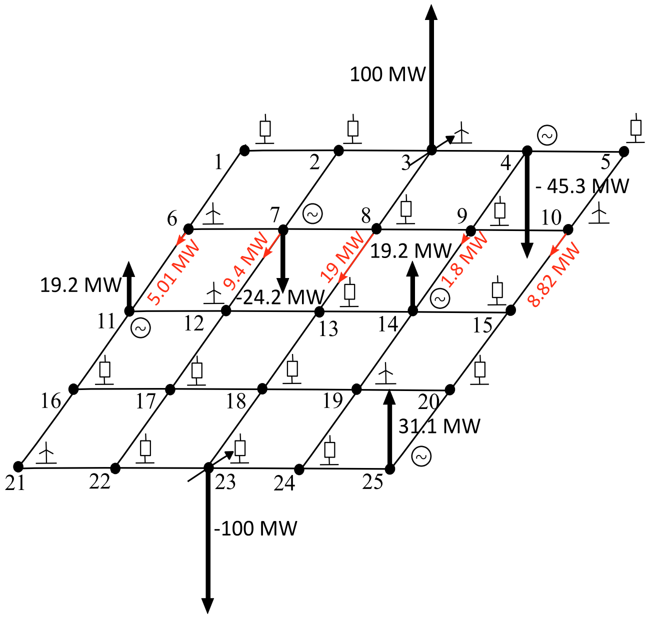

Fig. 8. Power flow with angle control *(not to scale)*

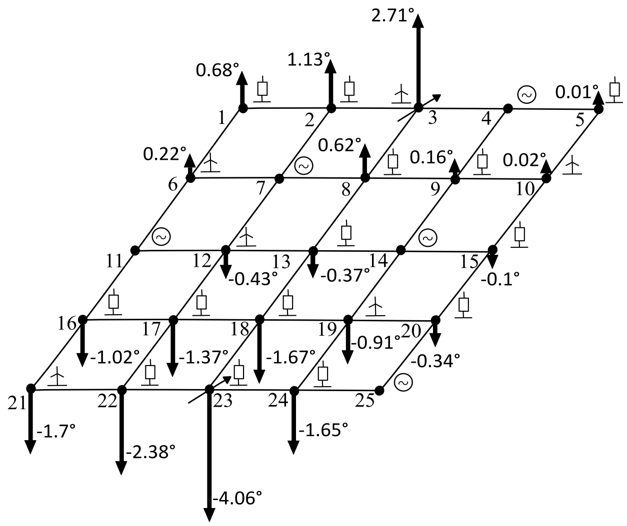

Fig. 9. Change of nodal voltage angles with angle control.

In Fig. 9, the changes in the angles of the nodal voltages are shown. There is no change of the voltage angles in the nodes 4, 7, 11, 14 and 25 since the storage power plants are in operation. These power plants are altering their generation or consumption to counter the initial changes made in node 3 and 23. Thus, it is now possible to avoid the heavy drilling of the grid resulting in a much reduced load flow and improved stability of the grid.

5. CONCLUSION

The examples described in the paper demonstrate how for an angle-oriented grid control the slack power stations "automatically" react to fluctuations in load demand as well as in the generation from renewable sources using the nodal voltage angle values.

These slack power stations are able to both consume, store and produce power depending on the situation. While doing so, the storage power stations continuously perform the required ancillary services like providing spinning reserve or primary control power, even in the case of storing energy. That way, the grid is completely regulated at all times and does not require immediate additional ancillary services, for example, from intermittent wind or PV power stations. Therefore, it is unnecessary to establish any controllability on such power stations, which in any case has proven to be inadequate.

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