Power Re-Dispatch Reduction with Nodal Voltage Angle Control in Storage Power Plants

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Abstract

Integration of fluctuating renewable energies into the power system has introduced new challenges in terms of providing grid stability. Nowadays, changes in the weather influences the influx of electrical energy into the network. Often, this upsets the balance between the supply and demand of electrical power, initiating re-dispatch measures to maintain grid stability. Such re-dispatch actions in Germany has cost approximately 402.5 million Euros in 2015 [1]. In this paper, a layout is proposed for a power station involving power electronic converters that can include storages for renewable energy taking different generation speeds into account. A novel method is utilized to control the electrical power distribution by these new storage power plants. All the control principles necessary involving spinning reserve, primary 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 storage power plants satisfy this rising demand with the power stations closest to the point of increasing consumption automatically producing the most power. Generating the most power close the point of consumption drastically reduces high power flows in transmission lines and the need for excessive power re-dispatch measures.

Keywords - *nodal voltage angle control, power electronic converters, power re-dispatch, storage power plants*

1 Introduction

One of the primary issues with current conventional power plants is their dependency on non-renewable fossil fuels. The depletion and resulting pollution from such sources demands viable renewable alternatives [2]. However, even the most prominent forms of these renewables such as solar and wind energy are highly intermittent in nature. This means that the power stations of the future must incorporate storage of renewable energy in feasible magnitudes to satisfy the consumer demand at all times [3].

To resolve these issues, a new type of power plant is described in this paper. These power plants will not possess any flywheels or rotating masses eliminating the need for frequency based control [4]. 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.

In the future, the number of conventional power plants will be reduced or they will disappear completely due to the lack of fossil fuels. Then, 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 known as the Nodal Voltage Angle control.

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 [5].
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 [6].
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).

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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. **Figure 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 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 instantaneous 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 to carbon dioxide, and the evaporator generates more steam. 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. 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 [7,8].

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.

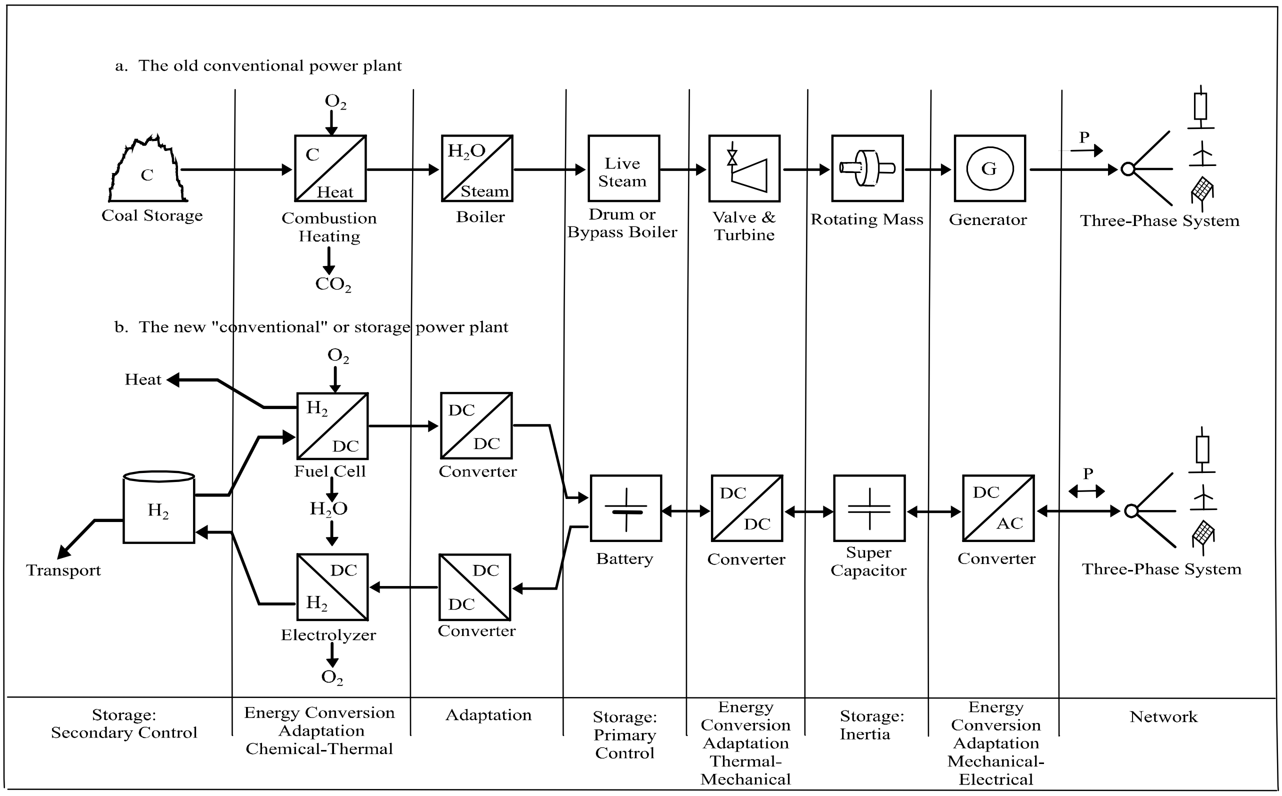

Figure 1 Comparison between the existing fossil fuel based power plant (a) and the new storage power plant (b)

Figure 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. 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 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 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.

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 us as exhibited by equation (2).

$$p_{s0} = p_{s0,scheduled} + p_{s0,secondary} + p_{s0,primary} \tag{1}$$

$$\underline{u_S} = u_s e^{j\varphi_u} \tag{2}$$

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.

3.2 Primary Control

Equations (3), (4), (5) and (6) in combination operate like a PLL circuit which measures the 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 50Hz.

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 5MW battery storage in Schwerin, Germany as a so-called "Droop Control" [9].

4 Nodal Voltage Angle Controlled 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 behavior) or an integral acting active power control (PV behavior). 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.

The operation of a storage (or slack) power plant under the influence of Nodal Voltage Angle control method is exhibited with the network in **Figure 2**. This consists of 25 equidistant nodes connected via transmission lines, each 50km in length and at a voltage level of 110kV. The line impedances are equal in magnitude, 0.3Ω/km, with a resistance to reactance ratio of 0.1.

It is assumed that each of the 14 loads consumes 10MW of active power. The total consumption of 140MW is equally shared by the 5 Slacks and the 6 PV Generators each producing 12.7MW to meet this demand. The network modeling and simulations are carried out in the software DigSILENT PowerFactory. The Slack and PV generators are modeled as AC Voltage Sources along with necessary control loops to represent the power electronic converters in place of conventional Synchronous or Asynchronous generators.

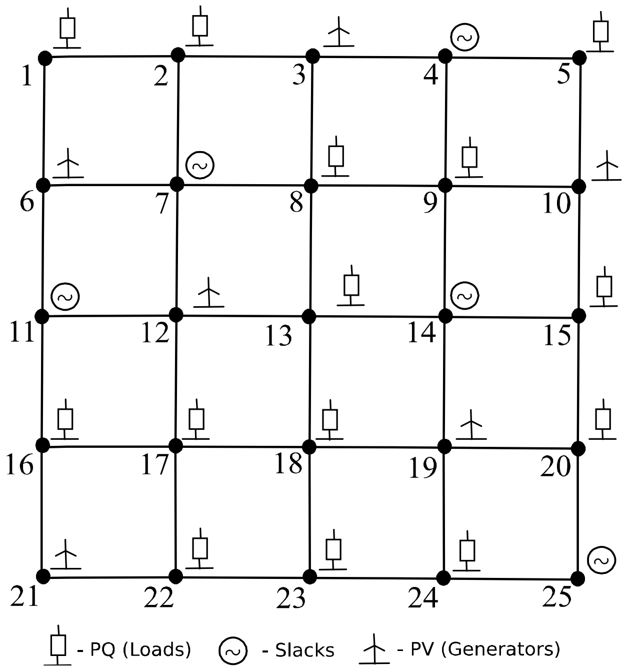

Figure 2 25 node example network

Figures 3, 4, and **5** show the voltage phasors of the load flow calculations respectively, for slack storage power stations, PV power stations, and PQ consumers. As shown in

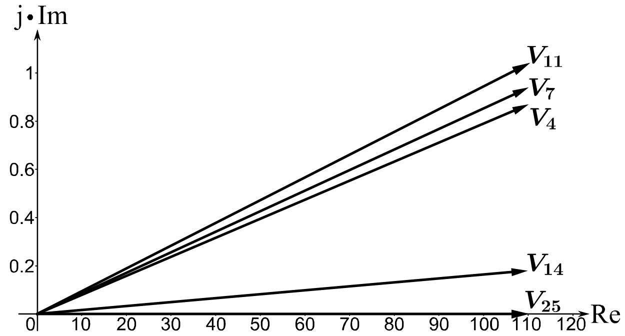

Figure 3 Voltage phasors of slacks (start of load flow)

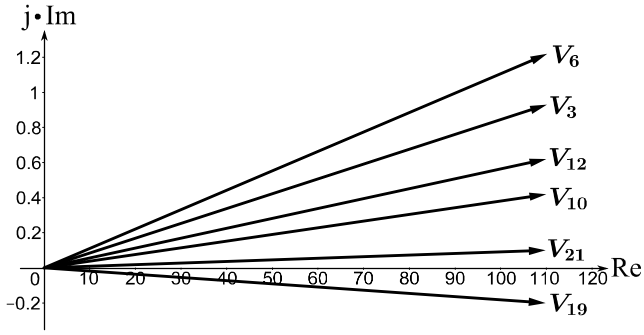

Figure 4 Voltage phasors of PV generators (start of load flow)

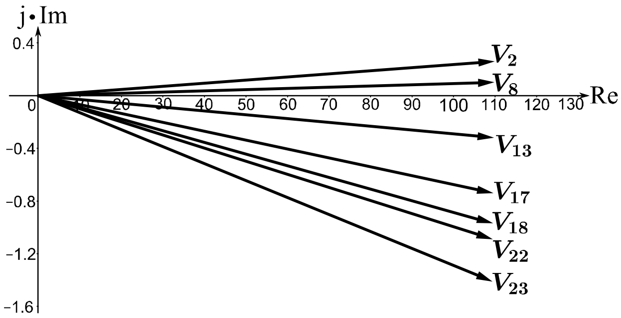

Figure 5 Voltage phasors of selected PQ loads (start of load flow)

the diagrams, the PQ consumer's voltage phasors follow the surrounding voltage phasors of slack and PV power stations, ensuring the power 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.

A new case of investigation is then added in which the consumption at node 13 is increased from 10MW to 110MW in increments of 10MW. 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).

Figure 6 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. This behavior is exactly analogous to the combined effect of spinning reserve and primary control. The type of primary control is load flow-oriented, since the neighboring 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 the remote storage power stations contribute little in terms of power supply.

Figure 7 exhibits the angle torsions of the non-slack nodes (PV generators and PQ consumers) from their initial operating point. 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 Figure 3).

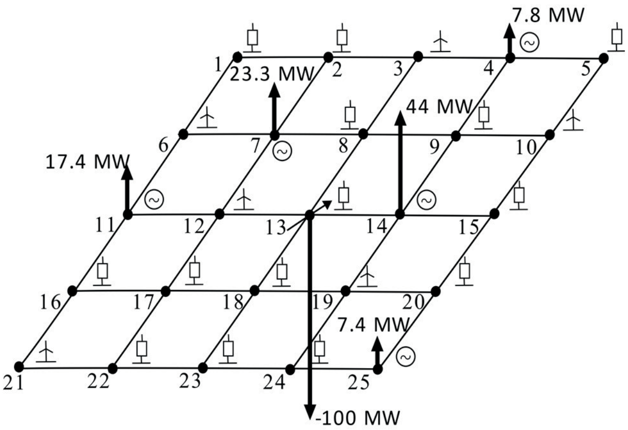

Figure 6 Increase in power consumption in node 13 and the resulting increases in the generation of every slack

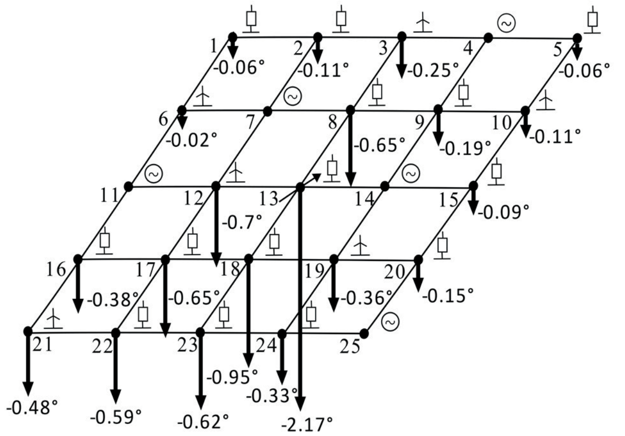

Figure 7 Increase in power consumption in node 13 and the resulting angle changes in PV Generators and PQ consumers

To observe the difference in the required re-dispatch measures under frequency and nodal voltage angle control, the following changes are made to the network.

The production by the PV Generator at node 3 is increased by 100MW while the consumption by the load at node 23 is increased by the same magnitude. Since the additional generation and production balance, the frequency remains unchanged. With the network being governed by frequency control, the primary controller does not act, and all the generators continue producing the same active power of 12.7MW. The additionally generated 100MW of active power at node 3 is transported completely to the south as shown in **Figure 8**. This results in a large power flow, which might overload the transmission lines, hence the grid requires significant re-dispatch measures to regain stability.

In **Figure 9** the changes in the angles of the phasors are shown with respect to the lone slack node, node 25. 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 100MW from the "North" to the "South".

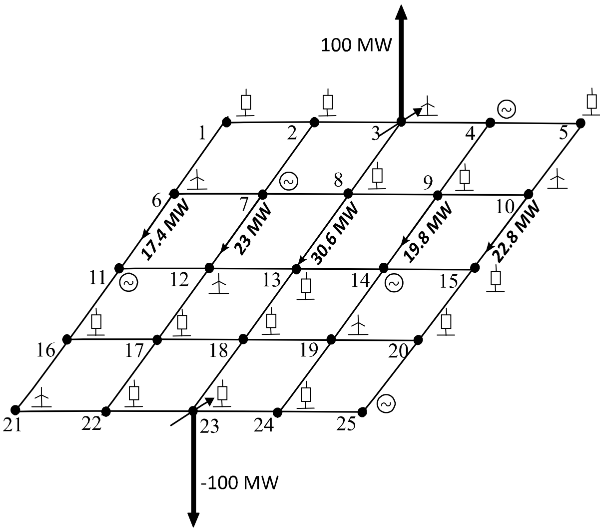

Figure 8 Power flow with frequency control *(not to scale)*

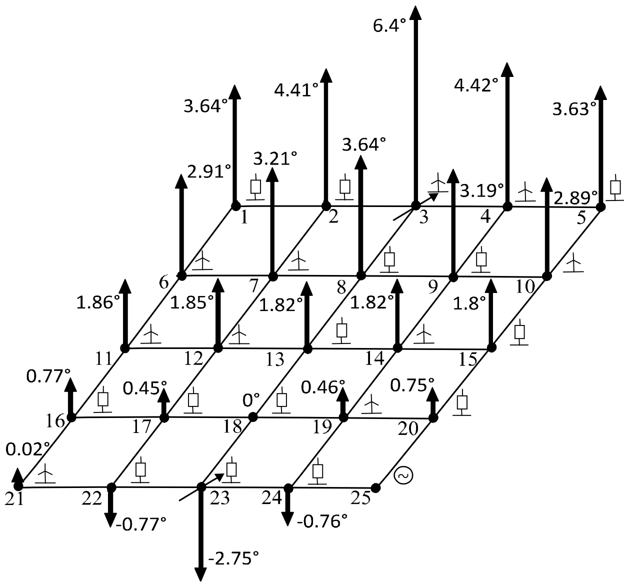

Figure 9 Change of nodal voltage angles with frequency control

Under nodal voltage angle control, all 5 storage power plants in their respective nodes are active. The ones in the north consume active power, while those in the south produce more power. Power flows through the lines are significantly reduced as exhibited in **Figure 10** thus reducing the need for extensive re-dispatch measures. As a result, the network can be kept in a safe and secure status using such control measures.

In **Figure 11**, again the changes in the angles of the voltage phasors are shown with respect to the slack node 25. In this case, since the storage power plants are now producing power, it is possible to avoid the heavy drilling of the grid resulting in a much reduced load flow.

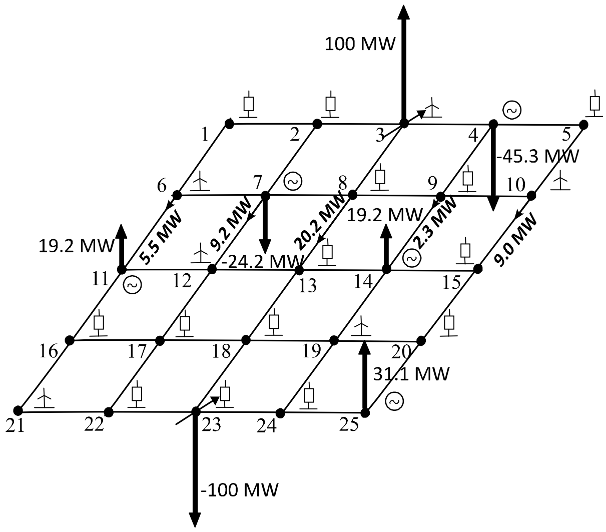

Figure 10 Power flow with nodal voltage angle control *(not to scale)*

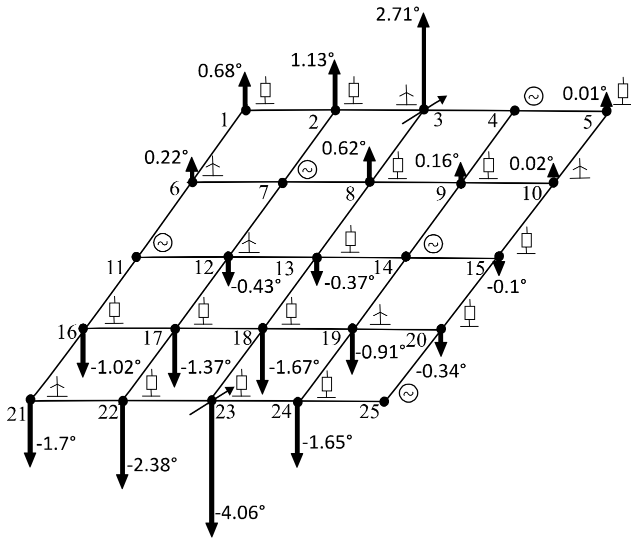

Figure 11 Change of nodal voltage angles with angle control

5 Conclusion

The flywheel mass-free storage power stations together with modern high performance grid control converter technology can function properly in both frequency and angle controlled networks. Within frequency controlled grids which still possess conventional flywheel masses, the new power stations can operate like ordinary power stations, performing all tasks of ancillary services like spinning reserve, primary control, secondary control, and scheduled production. 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 of an angle standard.

In addition, these new storage power plants will be able to store energy from renewable sources, making re-dispatch actions redundant in the network. That 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 complete the evaluation of this new method.

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