Nodal Voltage Angle Control of Power Systems with Renewable Sources, Storages and Power Electronic Converters

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***Abstract*— It is expected that the conventional power plants of today will soon be substituted by a complete inertia-less system. Such power stations will possess 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 existing today 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 there is an excessive consumption or generation of active power, all the slack power plants react instantly by either increasing their production or recharging their storages, with the ones closest to the point of disturbance providing the greatest response. In this manner, the excessive power flow from the production to consumption centers is reduced significantly avoiding the heavy overloading of the transmission lines. The behavior of this new control strategy is clearly described in this paper, taking into account the protection of such slack power plants when their maximum output power capacity is reached.**

Keywords—nodal voltage angle control, power electronic converters, slack power plants, storages

I. INTRODUCTION

We are currently in a state of transition, concentrating on the integration of renewable energy sources into the power system and the gradual elimination of conventional power plants using fossil fuels [1]. In Germany, the most prominent of these renewables are solar and wind power. However, since these sources of energy are fluctuating, the energy generated this way has to be stored on a larger scale in the foreseeable future. Currently electrical and chemical means of storage prove to be valid options for this purpose. These three new components of energy supply – wind, sun and storage – have one thing in common: they do not have flywheels or other rotating masses, because they are all connected to the grid via power electronic converters.

Today, there are only few converters and a larger number of power stations. Thus, the converters have to adapt to the 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 they can properly feed their angle-oriented regulating power into the grid. This way, the new components also function as power stations and can therefore be integrated into the system. When the number of conventional power plants reduces significantly or may even disappear completely, the artificial generation of an electrical frequency in the network as in the old world with inertia will be obsolete and a new method of grid control can be introduced – the nodal voltage angle control.

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:

- Large scale, highly dispersed power supply requires a three-phase network [2].
- Sudden load changes have to be fed instantaneously by spinning reserve from inertia or equivalent.
- 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 [3].
- 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.
- Following this, the scheduled power output of the plant has to be adjusted to replenish all used storages to their nominal value.
- 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, mostly running on fossil fuels. These power plants consist of a chain of components which is made of converters/adapters and storages operating at different speeds. Fig. 1a shows such an example of a coal power station's component chain.

Due to the increasing presence of renewable energies, conventional power stations have to drastically reduce their output at certain times 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 [4,5].

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

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would not only supply power during cold periods without wind and sun, but would also be able to store excess energy [6]. 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 supporting mode with constant grid frequency, signifying the transition 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 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 plants which is provided by the decrease in the speed of the rotating masses in the system.
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 where the opening of the steam valve is adjusted to increase the flow of live steam restoring the speed of the turbine prime mover.
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. 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. It may be refilled autonomously by the plant via the electrolyzer. This is similar to secondary control in conventional plants where the fuel governor accesses the coal store to increase the fuel input. However, the coal storage cannot be recharged automatically by the plant.

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 only act, when the consumption or production in the network changes

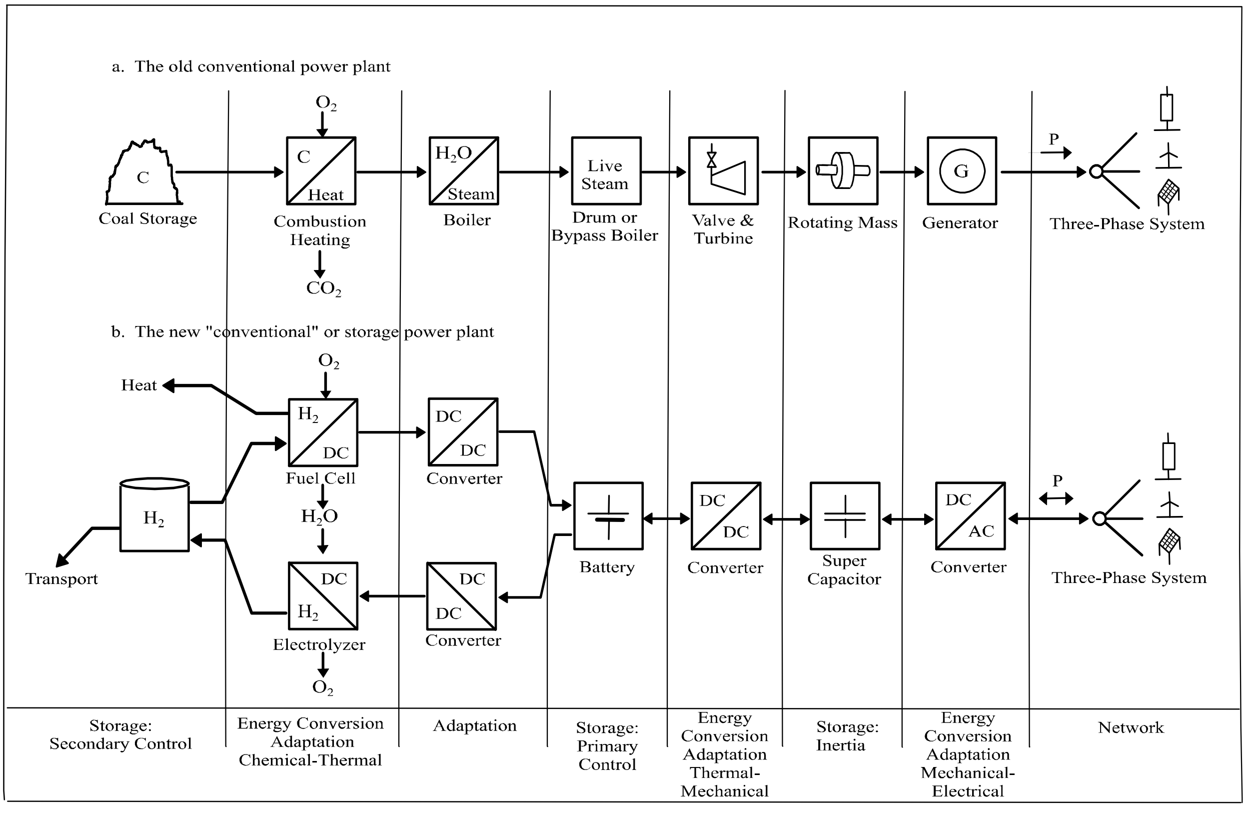

Fig. 1. Comparison between the existing fossil fuel based power plant (a) and the new storage power plant (b)

suddenly, in order to instantaneously respond and provide the necessary control actions autonomously.

Contrary to current power stations, which are only able to reduce their output to a certain minimum, this new type of power plant can actually reverse its output. In case of a production surplus from renewable resources there is a shock-free transition from fuel cell 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 STATION

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 changes in the supply frequency and its derivative with the supply of spinning reserve and primary control power [7]. 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).

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

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

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.

$$\Delta\omega_S = -\frac{1}{T_s} . (p_S - p_{S0}) \tag{3}$$

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).

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

$$\Delta\varphi_u = \Omega_0 \int \Delta\omega_S . dt \quad \& \quad \Omega_0 = 2\pi f_0 \tag{5}$$

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

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

$$p_{s0} = p_{s0,scheduled} + p_{s0,primary} = p_{s0,scheduled} - \frac{1}{\sigma_S} . \Delta\omega_S \tag{7}$$

As a result, the DC/AC converter can fulfil the task of the 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 plant participates in secondary control, the DC/AC converter's secondary control power, $p_{S0,secondary}$, will be raised until the Area Control Error (ACE) becomes zero and the supply frequency returns to its setpoint of 50Hz. If a supply delivering only primary control power is needed, then T_S is set to 0. Hence, the control rule becomes:

$$\Delta\omega_S = -\sigma_S . (p_S - p_{S0}) = 0 \tag{8}$$

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" [8].

IV. ANGLE REGULATED OPERATION OF A STORAGE POWER STATION

When the power supply system will mainly rely on storage power stations, "Watt's speed control" will not be required anymore. The three-phase supply can be operated at a constant frequency, for instance at 50 Hz. The tasks of grid control like spinning reserve and primary control 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. All the required information is provided using the given load flow. Storage power stations can operate either in grid-forming mode, as slack power stations (voltage source), or in grid-supporting mode, as 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 active power control (PV behavior). To that end, all power stations have to know the current voltage angle at their connected terminal with reference to the 50Hz 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 Bundes-anstalt (PTB) in Braunschweig, Germany once each day.

The mode of operation of this new type of grid control is best explained with an example network shown in Fig. 2. The grid consists of 25 equidistant nodes, each connected to either a generator or a load. The nodes are connected via transmission lines, each 50 km long and at a voltage level of 110kV. The line impedances are equal in magnitude with a resistance to reactance ratio of 0.1. There are 11 power stations, of which 5 are slack storage power stations. The other 6 are PV power stations i.e. generators at terminals where the active power (P) being supplied and the voltage (V) is known. The remaining 14 nodes are each connected to a PQ consumer i.e. loads at terminals where the active (P) and reactive power (Q) being consumed are known.

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. Each load also consumes 3.33Mvar of reactive power which is supplied later by the generators. Unfortunately, the reactive power results are not included in this paper due to space constraints. 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 behavior of power electronic converters replacing the conventional Synchronous or Asynchronous generators.

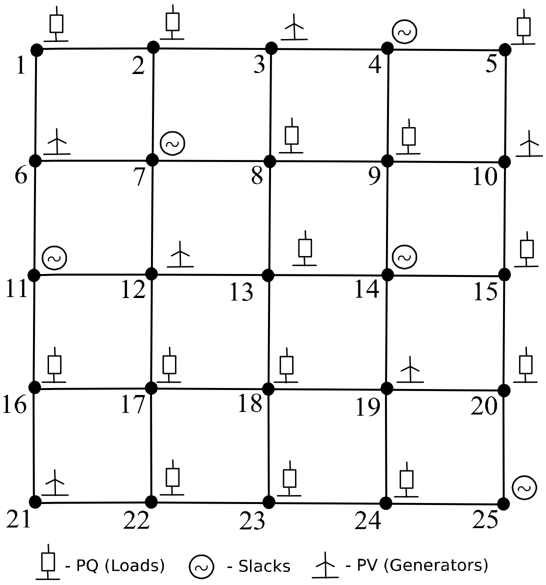

Fig.2. 25 node example network

Fig. 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 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 in voltage angles, the imaginary axis is shown in a heavily overstretched manner in this depiction.

A sample study is then carried out by implementing a ramp increase in both the production by the PV Generator at node 3 and the consumption by the PQ load at node 23 equally by 100MW. 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, along with some additional active power due to losses in the network and line resistance, is transported completely to the south as shown in Fig. 6. This results in a large power flow, which might overload the transmission lines, hence the grid requires significant re-dispatch measures to regain stability.

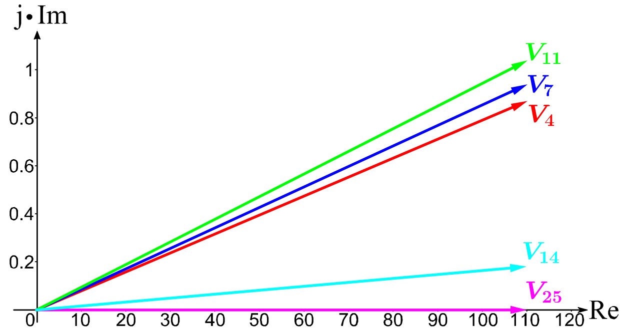

Fig. 3. Voltage phasors of slacks (start of load flow)

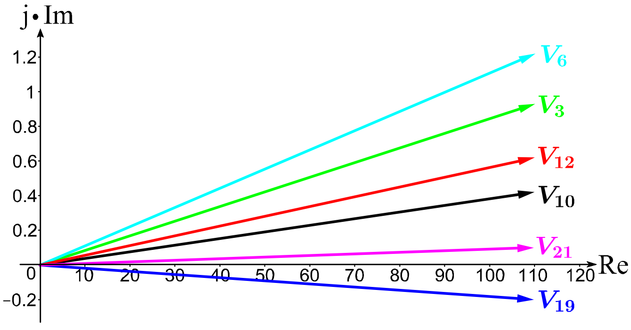

Fig.4. Voltage phasors of PV generators (start of load flow)

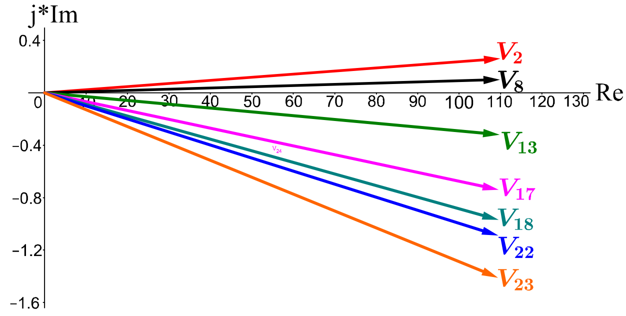

Fig.5. Voltage phasors of selected PQ loads (start of load flow)

In Fig. 7 the changes in the angles of the phasors are shown with respect to the 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".

In the next example shown in Fig. 8, the network is under angle control and all 5 slack storage power stations are active. The slacks in the "north" consume and those in the "south" produce power automatically to reduce the load flow values drastically. The excessive power generation in the North is utilized to recharge the storages of the nearby slacks at nodes 4 and 7. As indicated in Fig. 8, the storage plant at node 4 being closest to node 3 decreases its power output by the largest margin, from 12.7MW to −32.2MW, showing a change of −44.9MW. Meanwhile, the slacks at 11, 14 and 25 increase their production to support the load demand at node 23. The slack at node 25, being closer than the other two to node 23, shows the largest increase in power output, from 12.7MW to 44.1MW, thus showing a resulting increase of 31.4MW. Such response from the slacks under angle control, minimize the net power flow from north to south.

In Fig. 9, 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.

In nodal voltage angle control, the slack station closest to the point of increasing consumption or generation always provides the greatest response. However, this can lead to a dilemma because a slack cannot have unlimited generation or storage capability. Thus, in the next example, the network response is studied when two of the slacks showing the largest changes in power output so far reaches their limits. Once again the generation in node 3 and consumption in node 23 are ramped by the same magnitude of 100MW. The slack at node 25 is given a maximum generation limit of 25MW and the one at node 4 is given a maximum storage limit of −25MW. Thus, once these slack power stations reach their thresholds, they become a PV power plant, keeping their active power constant and releasing their voltage phasor, i.e. allowing their nodal voltage angle to change.

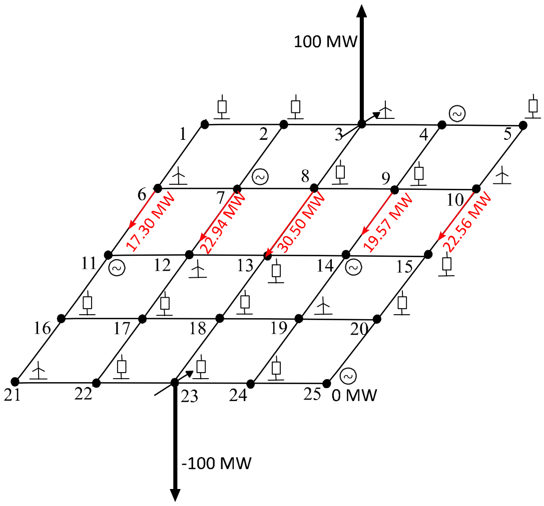

Fig. 6 Power flow with frequency control *(not to scale)*

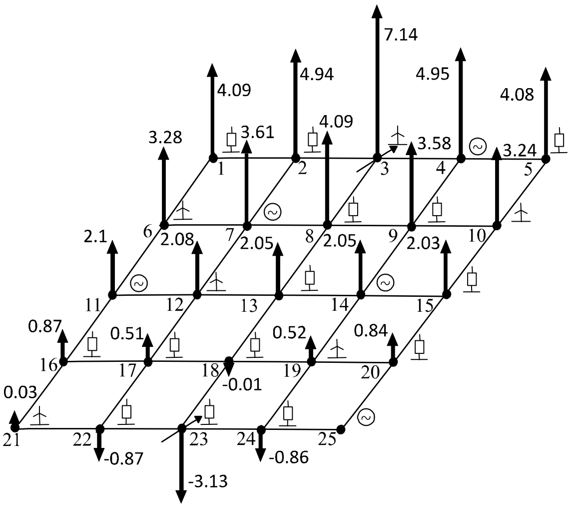

Fig. 7 Change of nodal voltage angles with frequency control

From Fig. 10 it can be seen that as soon as the slack in node 25 reaches its maximum limit, the two slack nodes 11 and 14 that are closest to it, start to increase their power output at a higher rate, signified by a higher slope in the graph. The same phenomenon occurs with the slack at node 7 when the one at node 4 reaches its limit since these two power stations are closer to each other. As a result, the three remaining storage power plants are now able to fulfill the total power requirement of the network and minimize undesired load flows in the process.

In Fig. 11, it is depicted that the additional power supplied by the plant at node 25 is now only 12.3MW, since it reaches its maximum limit of 25MW, compared to 31.4MW in the previous case. However, each of the plants at nodes 11 and 14 now produce an additional 22.5MW and 28.8MW, which are higher than their previous productions of 19.8MW and 19.3MW respectively. Thus, after the limitation, the duty of maximum power production is automatically shifted to the next nearest slack. The same scenario is repeated in the case of the slack at node 4. It can now only reduce its power output by −37.7MW instead of −44.9MW since it reaches its limit at −25MW. However, its cause is helped by the slack at node 7 which stores more power than it did in the case without limitation.

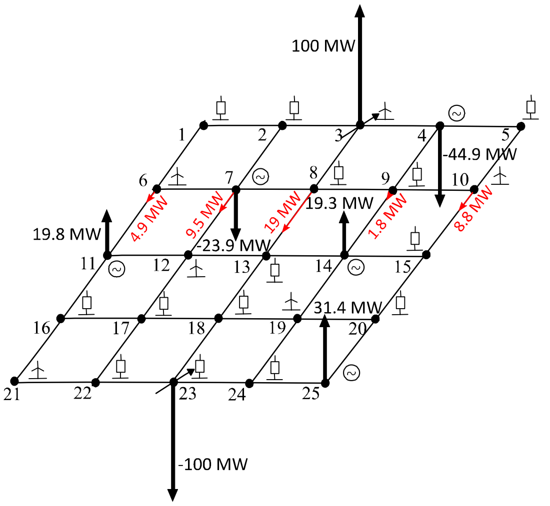

Fig. 8 Power flow with nodal voltage angle control *(not to scale)*

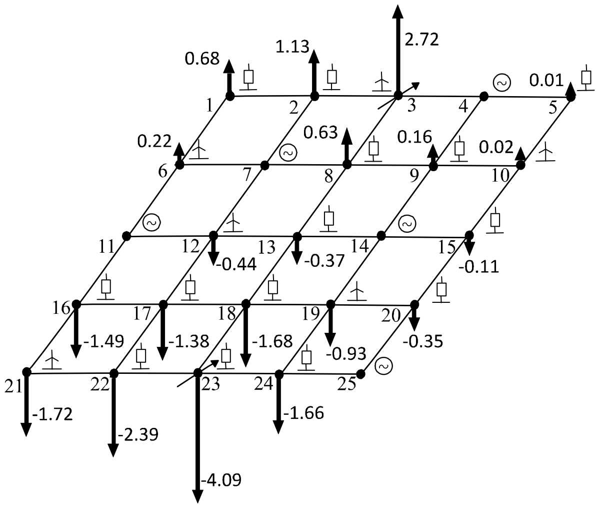

Fig. 9 Change of nodal voltage angles with angle control

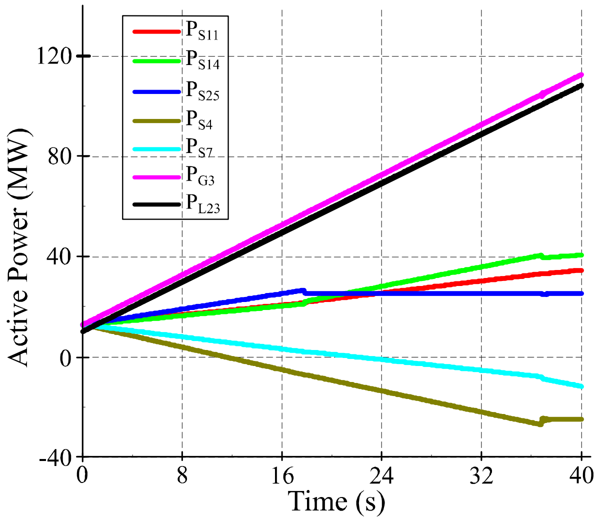

Fig. 10 Active power of slack nodes with limitation along with changing load & generator power

In Fig. 12, the voltage angles can be seen for the new scenario. Nodes 4 and 25 initially function as storage power plants and then behave as PV power plants once their power limits are reached. As a result, the two nodes undergo angular deviations of 0.25° and −1.28° respectively. In addition, due to the fewer number of slacks in the network,

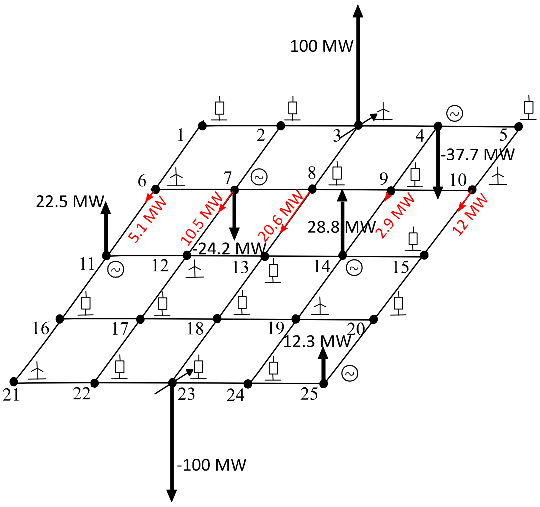

Fig. 11 Power flow with nodal voltage angle control and limitation in node 4 and 25

the individual angular deviations across the loads and PV power plants now have higher values compared to Fig. 9.

Due to the power limitation in two slacks in the network, the power flow through the lines increase compared to the previous case where angle control was implemented without any limitation. However, even with limitation in two slack power plants, the undesired power flows and the resulting possibility of overloading transmission lines is significantly reduced when angle control is implemented instead of frequency control as shown by table I-

TABLE I. POWER FLOW FOR DIFFERENT CONTROL METHODS

Lines	*Frequency Control* (MW)	*Angle Control* (MW)	*Angle control with limitation* (MW)
6 to 11	17.30	4.90	5.10
7 to 12	22.94	9.50	10.50
8 to 13	30.50	19.00	20.60
9 to 14	19.57	1.80	2.90
10 to 15	22.56	8.80	12.00
Sum of Power Flows	**112.87**	**44.00**	**51.10**

CONCLUSION

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 and secondary control as well as scheduled production. Moreover, they will be able to store energy from renewable sources, making re-dispatch actions redundant. In the future, involving angle-controlled networks, 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 with reference to an angle standard. When particular slack power plants in the network reach their maximum active power production or storage limit, the task of additional generation or accumulation can be shifted automatically to the neighboring stations. This way all possible future cases of application are covered, alleviating the process of further integration of renewable sources into the network. However, additional research will be required to estimate the total losses of this novel system and hence complete a quantitative comparative study with conventional power plants.

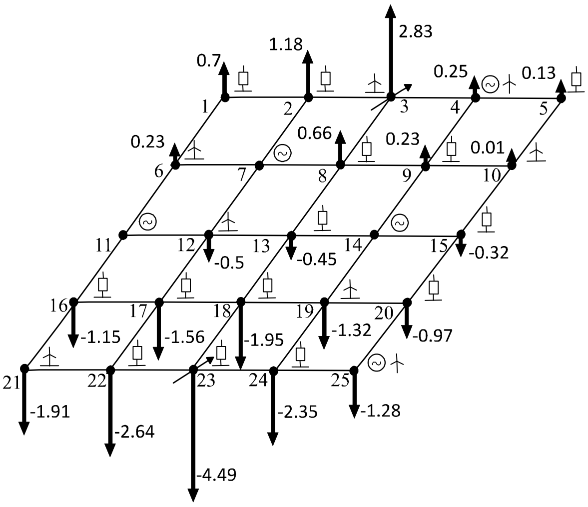

Fig. 12 Change of nodal voltage angles with angle control and power limitation in node 4 and 25

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