Dynamic Interaction of Conventional and Storage Power Plants in a Single Power System

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***Abstract*—It is expected that most of the conventional power plants of today will gradually be replaced by a complete inertia-less system. These new power stations will possess storages for different generation speed together with power electronic converters. However, some of the conventional thermal and hydro power stations will remain in operation and act as base power plants in the power grid. Thus, in this paper, a method is proposed which will govern the electrical power distribution in a network containing both conventional and the novel storage power stations. 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. With this control method in place, whenever there is a change in the power requirement of the network, the power plants react instantly with the ones closest to the point of disturbance providing the greatest response. The slack storage power plants are able to react faster than conventional ones and can also build up their power reserve during periods of excessive power generation from renewable sources. Not only does this method help to produce more power closer to the point of load demand reducing the stress on the generators located further away but it also improves the controllability of conventional power plants leading to lower system losses.**

***Keywords*—nodal voltage angle control, power electronic converters, storage power plant, storage, slack.**

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 generated energy 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 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.

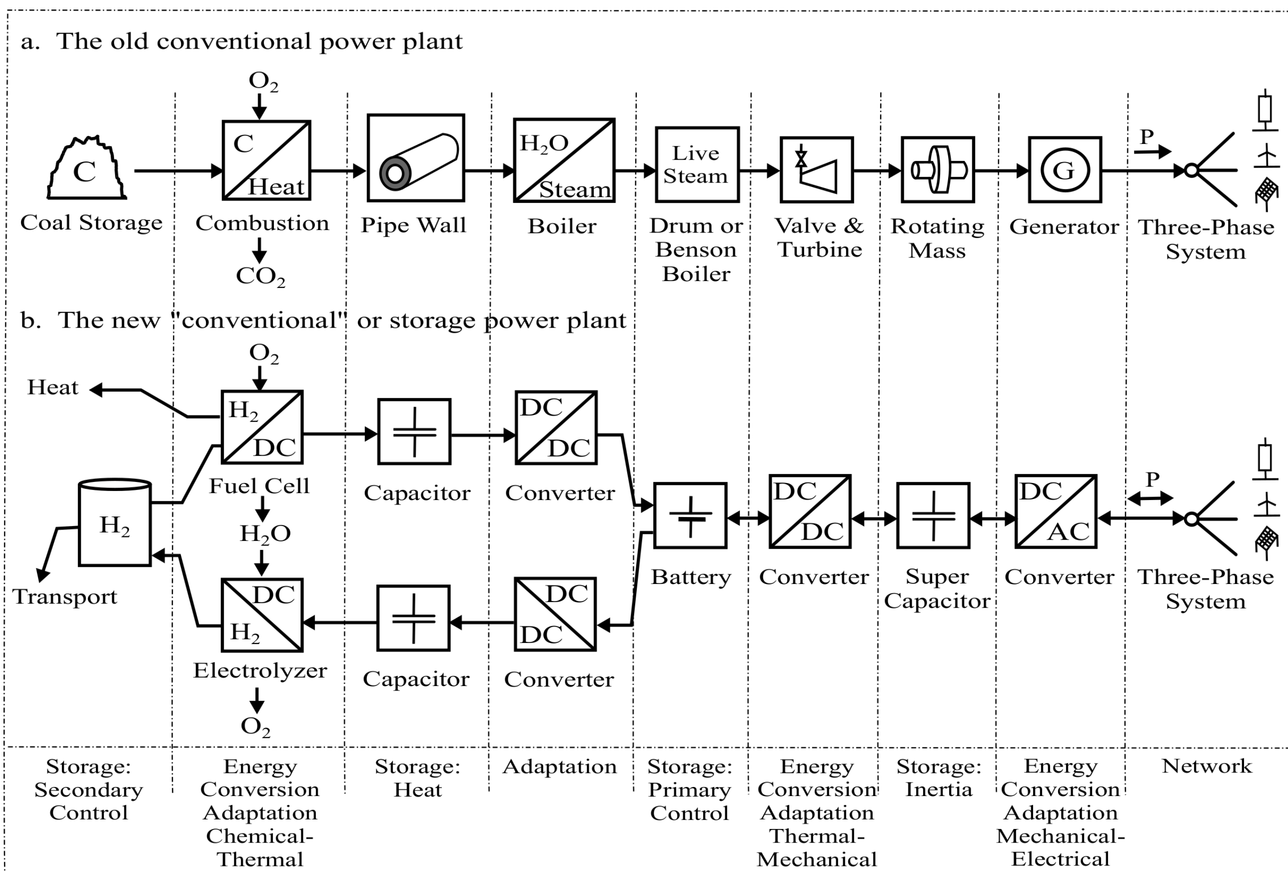

Fig. 1. Comparison between the (a) existing fossil fuel based and (b) new storage power plant

5) **Conversion/adaptation:** The DC/DC converter, on the upper branch between the fuel cell and the battery, adjusts the required voltages enabling the charging current to flow from the fuel cell to the battery. The fuel cell's control unit increases its activity and synthesizes more water from hydrogen and oxygen and in the process produces more energy to replenish the battery voltage and satisfy the power demand in the network.
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. The capacitor between the DC-DC converter and the fuel cell stores some energy and is analogous to the heat stored in the boiler walls of a steam power 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 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 renewables or decrease in load demand, there is a shock-free transition from fuel cell to electrolyzer operation to store excess power. 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. Angle Regulated Operation of Conventional and Storage Power Plants

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 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 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 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, i.e. generators at terminals where the voltage magnitude ($|V|$) and angle (ϕ_u) are known. The other 6 are conventional power stations with known active power (P) and voltage (V) at the terminals. Out of these 6 power plants, 4 are conventional hydro (H) and the other 2 are steam (T) power stations. 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 10 MW of active power. The total consumption of 140 MW is equally shared by the 5 Slacks and the 6 conventional generators each producing 12.7 MW to meet this demand. Each load also consumes 3.33 MVAR 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 storage power plants 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. The composite model for this is shown in Fig. 3. Each busbar

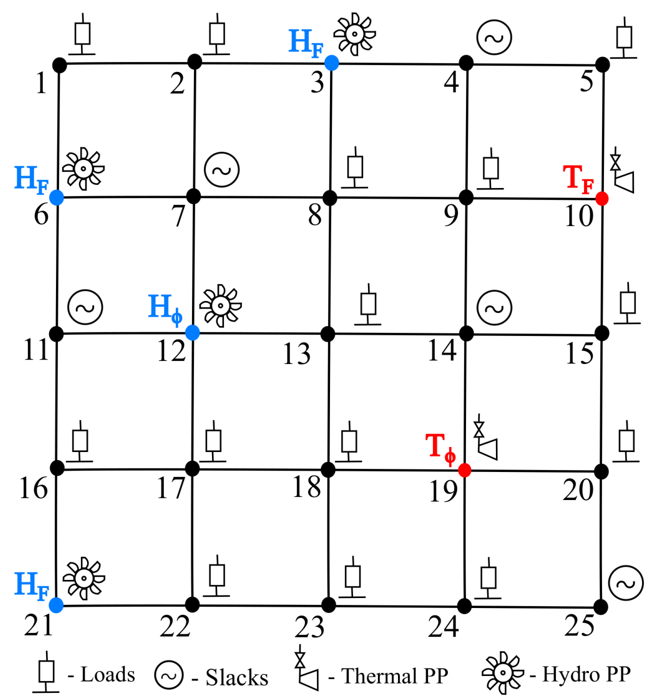

Fig. 2. 25 node example network

housing a slack is also connected to a power measuring (class name: *StaPqmea) and voltage measuring device (class name: *StaVmea). The required signals are passed to the angle controller as well as the internal model containing the structure for the supercapacitor, battery, fuel cell etc. The voltage magnitude and its angle obtained as the output of the angle controller are fed as inputs to the AC Voltage source.

The detailed model for the angle controller of the slacks is shown in Fig. 4. The opened position of the switch ensures that irrespective of the value of the error signal arising from the difference between the active power signal and its reference value, i.e. p and p_0, the change in angular speed $\Delta\omega_1$, as well as the change in primary control power Δp_{prim}, will be 0. As a result, there will be no change in the voltage angle, i.e. $\Delta\phi_u$ will be zero. The voltage angle will remain unchanged at its starting value from the initial loadflow throughout the course of the dynamic simulation. This will enable the slack node to keep its initial voltage angle. The feedback loop above Δp_{prim}, is needed for droop stability and prevent the system from oscillating excessively during the transient state.

The composite model of the conventional thermal power plant being used is shown in Fig. 5. The voltage measuring device is able to measure the real and imaginary components of voltage at the busbar to which the generator is connected. These components are used to calculate the voltage angle inside the governor. In the event of a disturbance in the network, the change in the voltage angle is calculated. This change along with information regarding the scheduled power flow is used to determine a new valve position which alters the flow of steam into the turbine. The turbine receives information regarding the changed valve position from the governor and the pressure of steam from the boiler. Using these signals it is able to generate mechanical power as output which is next fed to the generator to produce the needed electrical power to counter the initial disturbance.

The composite model of the conventional hydro power plant being used is shown in Fig. 6. It uses the same governor and AVR structure as that of the steam power plant. The primary difference between the two power plants is in the modeling of the penstock for the hydro power station and the different turbine structures being used. In this case, a change in the voltage angle resulting from a disturbance in the network is used to change the valve position which determines the water flow rate at the end of the penstock. This in turn determines

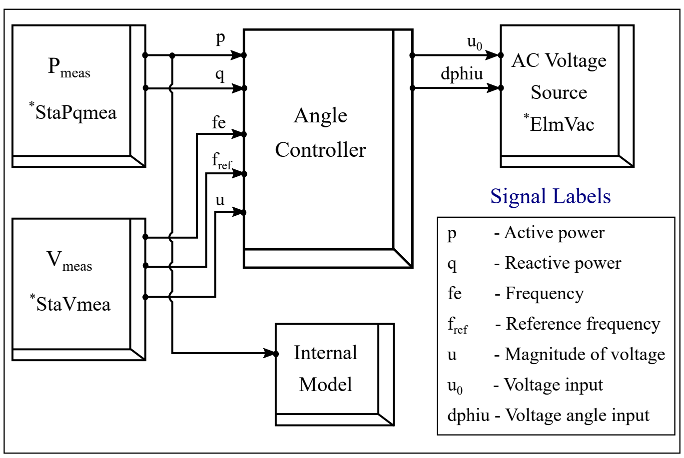

Fig. 3. Composite model for the AC Voltage Source representing a storage power plant

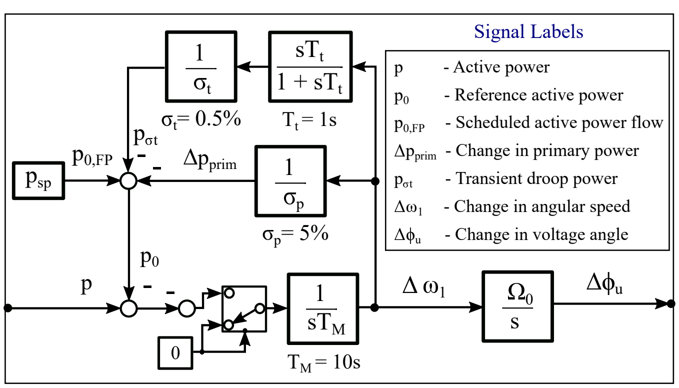

Fig. 4. Common model for the angle controller of the slack storage power plant

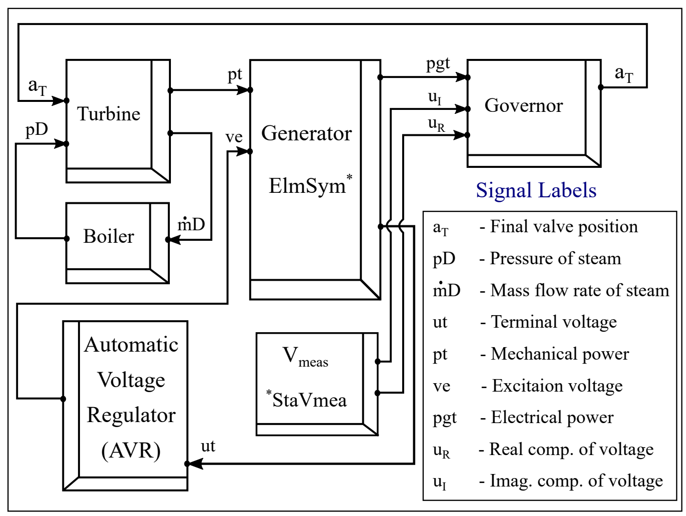

Fig. 5. Composite model for the synchronous generator representing a thermal power plant governed by angle control

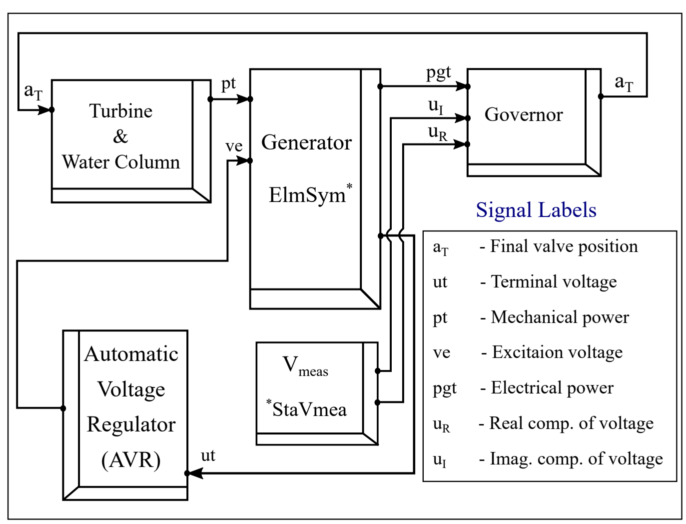

Fig. 6. Composite model for the synchronous generator representing a hydro power plant governed by angle control

the mechanical power output of the hydro turbine and hence the electrical power output of the generator. Every component shown in the composite models in Fig. 5 and 6 has a more detailed structure. However, they are not further discussed in the paper due to lack of space.

A new case study is then carried out in order to investigate the dynamic behavior of the three types of power plants in a single network as shown in Fig. 2. A ramp is implemented to increase the power consumption at the central load, node 13 from 10 MW to 110 MW between the time window of 10 s to 90 s. 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 active power controller model shown in Fig. 4 is used for every slack storage power plant in the network. Two of the conventional power plants in node 12 (H_ϕ) and 19 (T_ϕ) are provided with the angle control structure shown in Fig. 6 and 5 respectively. The other four conventional power stations have today's typical frequency governed structure (T_F) and (H_F).

It can be seen from Fig. 7 that, following the increase in power consumption at load 13, there is a significant decrease in its nodal voltage angle. A similar trend can be noticed for the load nodes that are near to node 13. For example, the next largest changes in the nodal voltage angles are seen in node 8 and 18 since they are close to node 13. However, the changes in the voltage angles of the loads that are further away from the load changing node, for example node 2, are much smaller.

Similar results can also be noticed in Fig. 8 for the voltage angles of the four frequency governed conventional generators. Since the frequency is at a constant value of 50 Hz under angle control mode, these generators continue to produce a constant active power despite the increased power demand in the network. As a result, their voltage angles change in accordance to those of the nearby loads to keep the angles constant between the two. However, the two conventional generators in node 12 and 19, shown in Fig. 9, possessing the angle control structure, are able to react to the voltage angle change and produce more power to satisfy the increased power demand in node 13. As a result, the voltage angle in these two nodes does not decrease as much as those of the four other generators and continue to remain largely positive in relation with the voltage angles of the nearby loads.

Fig. 9 also shows that the grid-forming converters of slack storage power stations are always able to keep their voltage angles constant. Since the voltage angles change more for loads closer to load 13 and stay constant for slacks, the resulting increase in the angles between these two enable the slacks near load node 13 to produce more active power compared to others. Hence, following a disturbance in a network governed by nodal voltage angle control, the power stations close to the point of disturbance will provide the necessary ancillary services. As opposed to frequency control, this will allow the power stations further away to remain undisturbed.

Fig. 10 shows the power increase of the consumer at the central node 13 and the corresponding reaction of the angle

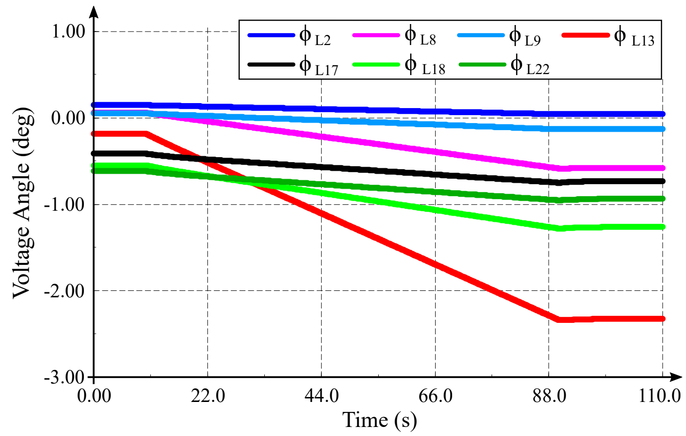

Fig. 7. Nodal voltage angles of all PQ loads

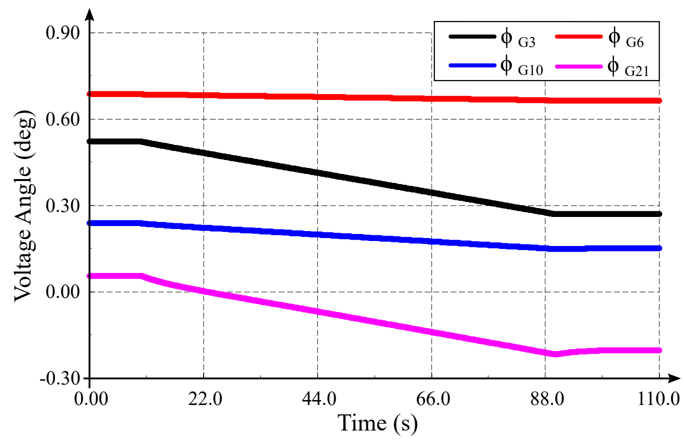

Fig. 8. Nodal voltage angles of all frequency governed generators

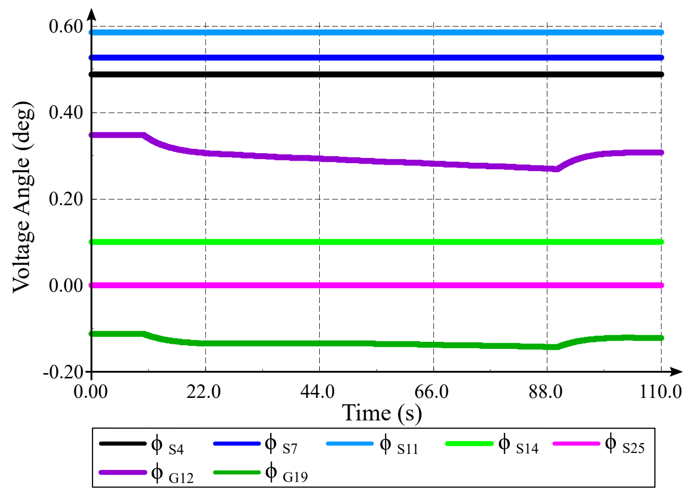

Fig. 9. Nodal voltage angles of all slack storage power plants and angle controlled generators

controlled power stations. It shows how each of the power plants supply the additional required power according to their electrical proximity to the consumer. The slack storage power station at the neighboring node 14 provides the maximum increase in active power output. This is followed by the hydro power station at node 12. After these, there is the slack storage power station at node 7 and the thermal power plant at node 19. Slack 25 has the lowest increase in power output because it is

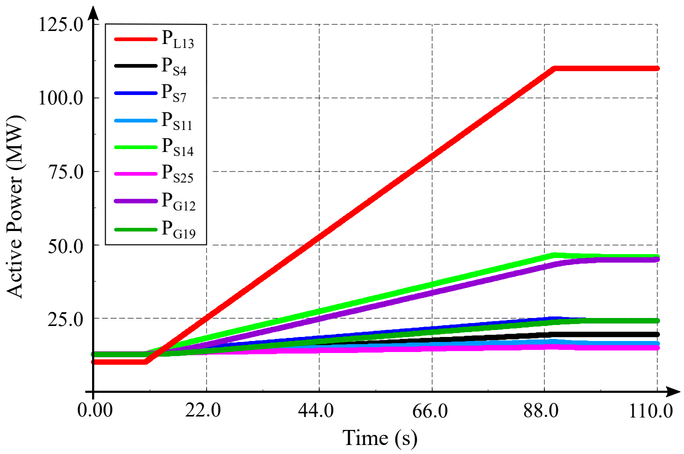

Fig. 10. Response of storage power plants and angle controlled conventional generators to increasing power demand in load 13

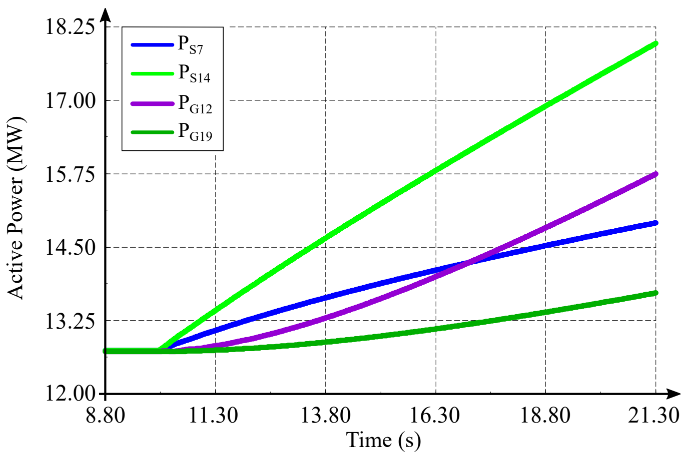

Fig. 11. Response speed of slack and angle controlled conventional generators

the farthest angle controlled generator from load 13. Due to the resistance in the transmission lines, there will be some losses during the power flow and the total additional power supplied will be greater than the additional demand of 100 MW. Such behavior of the angle controlled power plants is analogous to the combined effect of spinning reserve and primary control. This type of primary control is load flow oriented, since the neighboring storage power stations have a greater load to bear than the remote ones. Hence, 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. 11 shows how quickly the angle controlled power plants can respond to the increased power demand in load 13 in comparison to the storage power stations. As indicated by the two linear power output lines, the storage power stations are able to respond immediately since they have a very low inertia. The conventional power plants react slower and when they reach their maximum power output, the storage power stations automatically reduce their output so the total generation balances the total consumption in the network.

With this type of control method it is also possible to limit the maximum power output of the thermal or hydro power plants and improve their controllability. For example, during periods of excess generation from renewable sources or reduced load demands, the power output of conventional generators cannot be usually lowered below 60% of their rated power. Operating below this threshold leads to high losses since the cost of keeping the power plant operational becomes too high compared to the generated output. In such cases, a network with a combination of storage and conventional power plants would be ideal. The storage power plants would be able to reduce their power output and even store excessive power if needed. This would enable the conventional plants to always operate above their minimum threshold and in the process lower the system operational losses.

Conclusion

The investigations in this paper prove that the flywheel mass-free storage power stations together with the modern high-performance grid control converter technology can function coherently with conventional power plants. With the system being governed by voltage angle control, the generators react autonomously to load changes and disturbances and satisfy the network demand. In addition, the performance of storage power plants under this control method provides the opportunity of further integration of renewable sources and improves the controllability of conventional stations. However, additional research will be required to estimate the total losses of this novel system and hence complete a quantitative comparative study in relation to the current power system.

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