Dynamic Behavior 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 independent system. These new plants will possess storages for different generation speed together with power electronic converters. However, some of the conventional thermal and hydro power plants will remain in operation and act as base power plants in the electrical 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 inertia-less storage 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. 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 boost 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 operational 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. In Germany, the most prominent of these renewable sources are solar and wind power. However, since these sources are intermittent in nature, leading to higher forecast errors [1], 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 the energy supply – wind, sun and storage all have one thing in common. They do not have rotating masses because they are all connected to the grid via power electronic converters.

Today, there are only a few converters and a greater number of conventional power plants. Thus, the converters have to adapt to the rotating 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 plants 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 could become obsolete. A new method of electrical grid control can then be introduced, known as the nodal voltage angle control.

II. THE NEW “CONVENTIONAL” OR STORAGE POWER PLANT

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, within a few seconds, by the primary control power. To that end, storages for primary control power are necessary.
- Primary control power, within a few minutes, 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 plants, 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 plant’s component chain.

Due to the increasing presence of renewable energies, conventional power plants have to drastically reduce their output at certain times to give way to renewables [3]. To that end, the amount of power supplied has to be lowered and the control rate has to be raised. Every power plant using fossil fuels today has to fulfill these requirements [4].

A new kind of “conventional” power plant 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 plants would not only supply power during cold periods without wind and sun, but would also be able to store excess energy [5]. At the same time, these power plants will have to operate during a transitional period with a rotating mass-based power supply from power plants existing today. If the power supply is completely converter-based they can be used in either grid-forming or grid-supporting mode with a constant grid frequency, signifying the transition to angle control.

Fig. 1b shows the component chain of a new type of rotating mass-free power plant, which can work in grid-forming mode. Its mode of operation will be demonstrated with an example of a step increase in the active power requirement at the DC/AC converter:

1) **Conversion/adaptation:** The step increase in the active 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 supercapacitor instantaneously accesses its stored electrical energy and supplies this as active output power. A capacitor is chosen for this purpose as it can instantaneously supply large magnitudes of power. The voltage of the supercapacitor decreases and this corresponds to the amount of its stored energy. These features are similar to that of the spinning reserve in conventional power plants, which is provided by a decrease in the speed of rotating masses in the system.
3) **Conversion/adaptation:** The downstream DC/DC converter’s governor (between the battery and the supercapacitor in Fig. 1b) has to keep the capacitor voltage constant. To this end, it accesses the battery increasing the battery output power within a few seconds. As a result, the capacitor charging current increases and this recharges its energy storage. These properties are similar to that of the primary control of conventional power plants where the opening of the steam valve in the boiler 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 DC/DC converter, on the upper branch between the fuel cell and the battery, adjusts the required voltages enabling the charging current

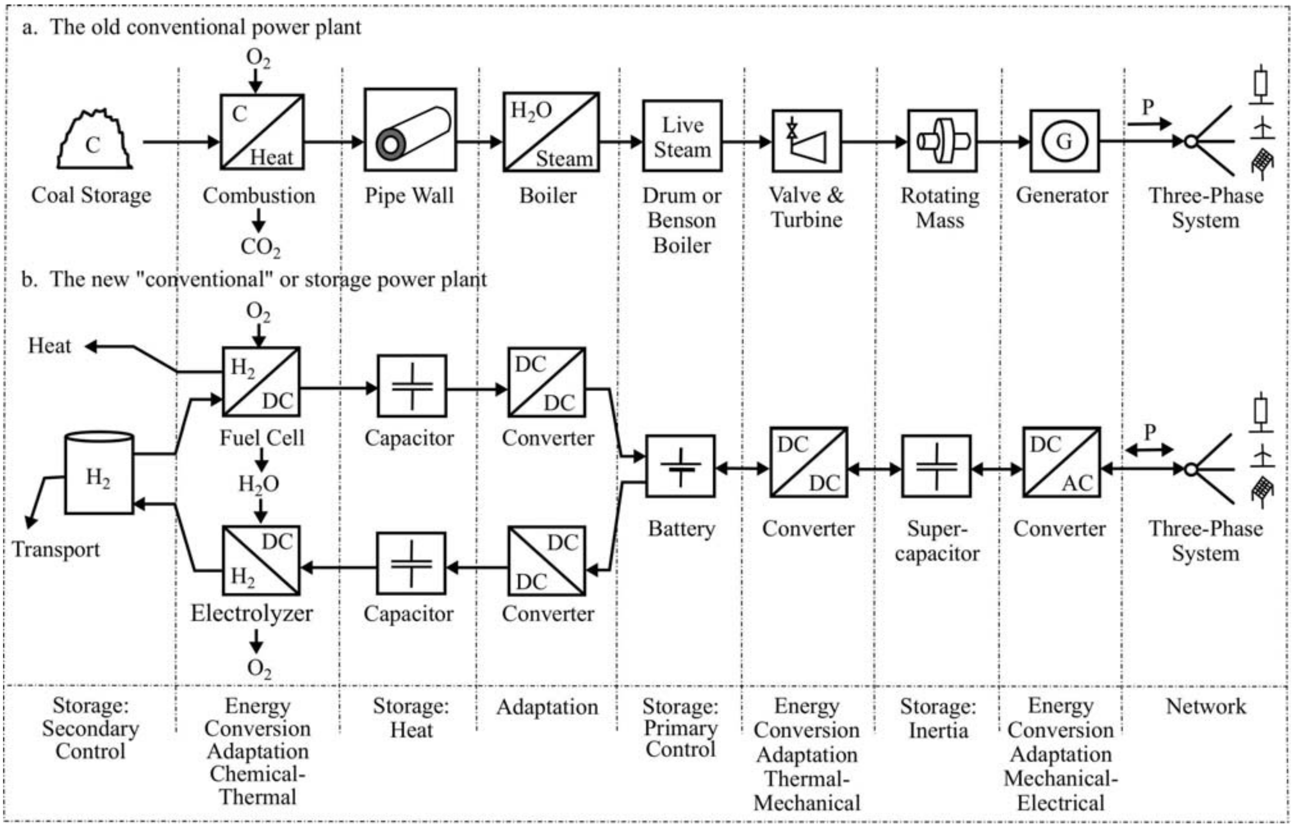

Fig. 1. Comparison between the (a) existing fossil fuel based and (b) new storage power plant

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 storage as well as satisfy the power demand in the network.

6) **Storage:** The fuel cell's control unit accesses the hydrogen storage within a few minutes 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 reloaded 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 supercapacitor or battery storages only act, when the consumption or production in the network changes suddenly, in order to instantaneously respond and provide the necessary ancillary services autonomously. Contrary to current power plants, which are only able to reduce their power output to a certain minimum, this new type of power plant can actually reverse its output. In case of a production surplus from renewable sources 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. Thus, this new type of "conventional" plant may be called a Storage Power Plant.

III. ANGLE REGULATED OPERATION OF CONVENTIONAL AND STORAGE POWER PLANTS

When the power supply system will mainly rely on storage power plants, "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 plant'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 plants can operate either in grid-forming mode, as slack power plants (voltage source), or in grid-supporting mode, as PV power plants (current or power source). To this end, the power plants have to know the current voltage angle at their connected terminal with reference to the 50 Hz angle standard of their control area. This can be done by using an accurate radio-controlled quartz clock. The features of this clock would not affect the daily operation of the slack power plants and it would simply be used to reset the reference point of the system to its initial value once a day correspondingly adjusting the angles of the slack voltage phasors. For this purpose the clock can be synchronized via the time signal transmitter, DCF77, of the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig, Germany once each day. These features are still present in the current conventional power plants with a certain time delay from either an integral acting angle control (slack behavior) or active power control (PV behavior).

The mode of operation of this new type of grid control can be 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. Such a squared grid is used to allow the simulation results to remain unaffected by the complex structure of the grid itself. This will become more apparent once Fig. 10 is analyzed at the end of this section.

There are 11 power plants, of which 5 are slack storage power plants, i.e. generators at terminals where the voltage magnitude ($|V|$) and angle (ϕ_u) are known. The other 6 are conventional power plants with known active power (P) and voltage magnitude ($|V|$) at the terminals. Out of these 6 power plants, 4 are conventional hydro (H) and the other 2 are steam (T) power plants. 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 and controls are not included in this paper due to space

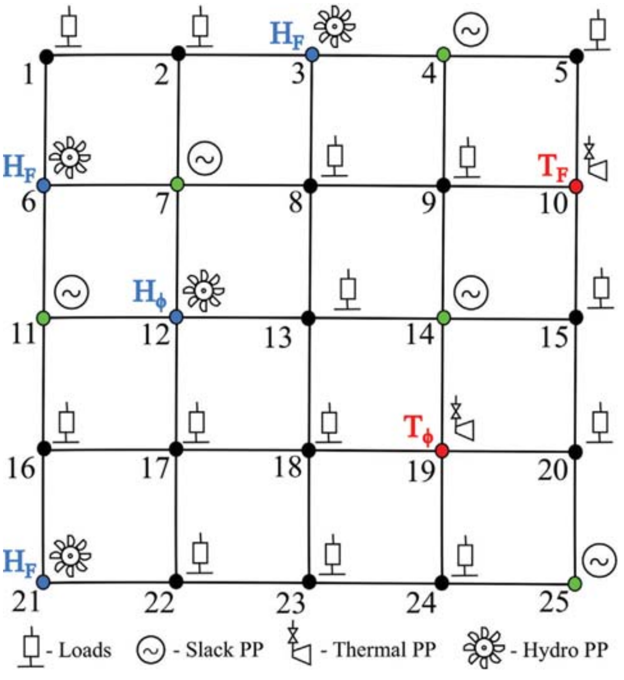

Fig. 2. 25 node example network

constraints. However, it can be mentioned that the system has an improved dynamic between reactive power and voltage under the new control method due to the voltage stabilizing ability of the slacks.

The network modeling and dynamic RMS 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 frame for this is shown in Fig. 3. Each busbar housing a slack is also connected to a power and voltage measuring device. 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 outputs of the controller are fed as inputs to the AC Voltage source.

A simplified model for the angle controller of the slack power plants is shown in Fig. 4. The opened position of the switch ensures that irrespective of the error signal magnitude arising from the difference between the active power signal and its reference value, i.e. p and p_0, the change in angular speed $\Delta\omega_1$ 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 composite frame for the conventional thermal power plant with an angle controlled governor 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 model 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.

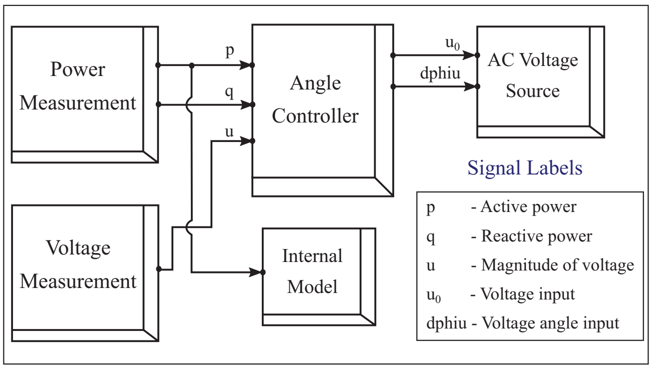

Fig. 3. Composite frame for the AC Voltage Source representing a storage power plant

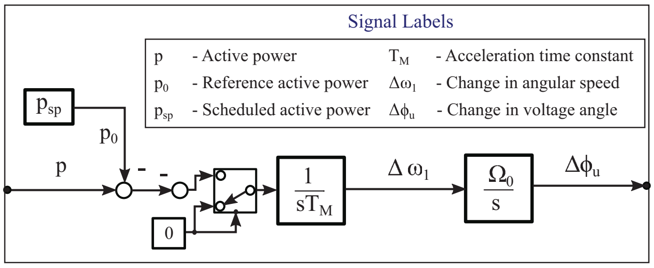

Fig. 4. Model definition for the angle controller of the slack storage power plant

The composite frame for 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 plant 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 the mechanical power output of the hydro turbine and hence

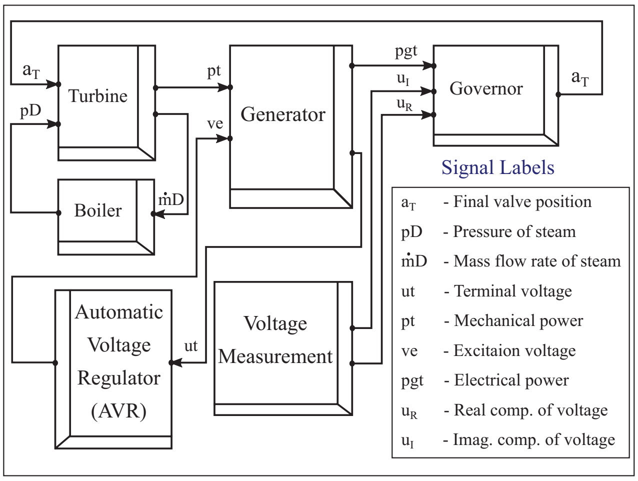

Fig. 5. Composite frame for the synchronous generator representing a thermal power plant governed by angle control

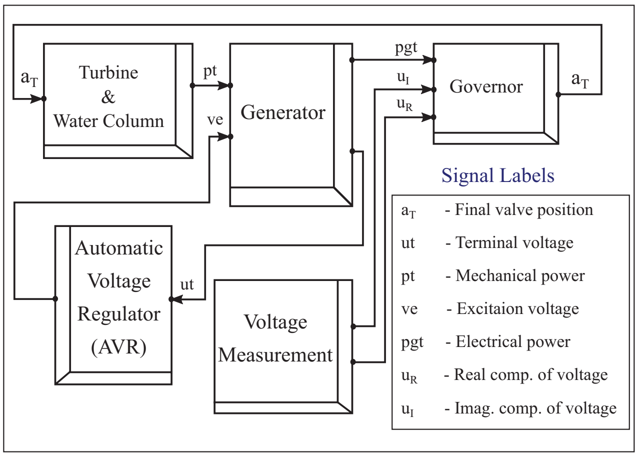

Fig. 6. Composite frame for the synchronous generator representing a hydro power plant governed by angle control

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 plants 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 plants 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 an angle controlled governor, 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 storage power plants 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 enables 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 plants close to the point of disturbance will provide the necessary ancillary services. As opposed to frequency control, this will allow the power plants further away to remain undisturbed.

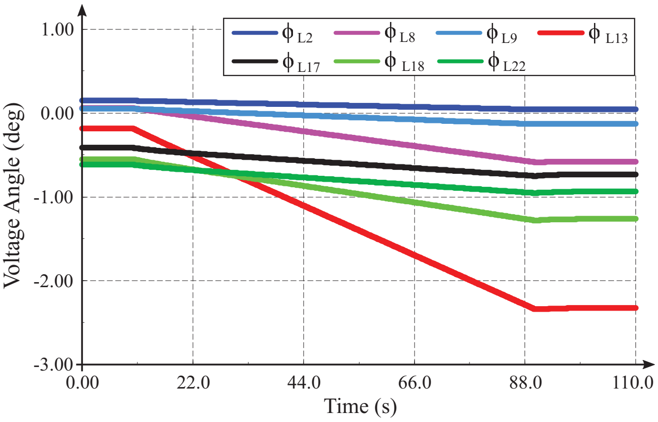

Fig. 7. Nodal voltage angles of all PQ loads

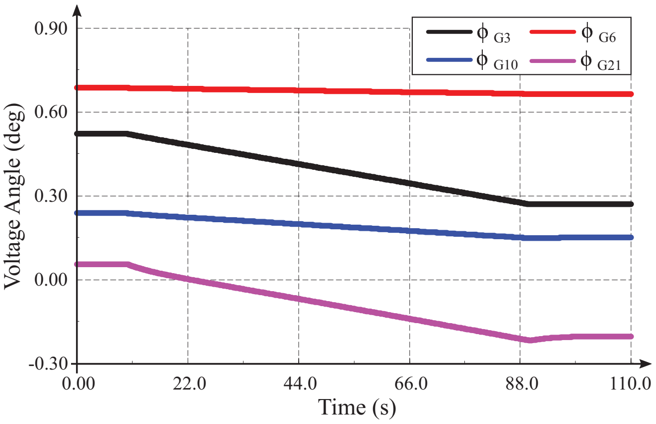

Fig. 8. Nodal voltage angles of all frequency-governed generators

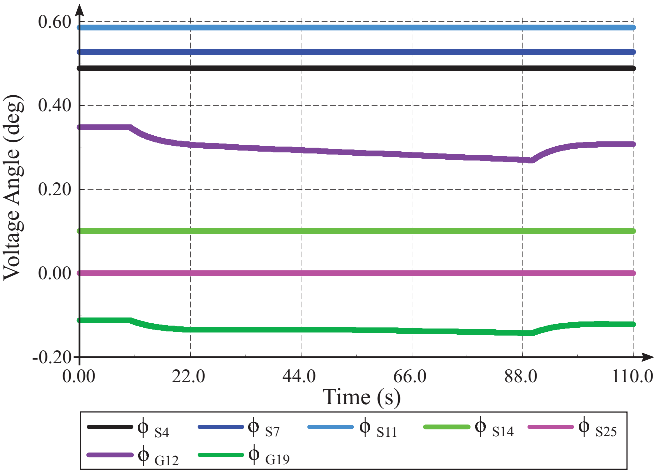

Fig. 9. Nodal voltage angles of all slack storage power plants and angle controlled generators

Fig. 10 shows the power increase of the consumer at the central node 13 and the corresponding reaction of the angle controlled power plants. It shows how each of the power plants supply the additional required power according to their electrical proximity to the consumer. Due to the resistance in the transmission lines, there are some losses during the power flow and the total additional power supplied is 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 plants have a greater load to bear than the remote ones.

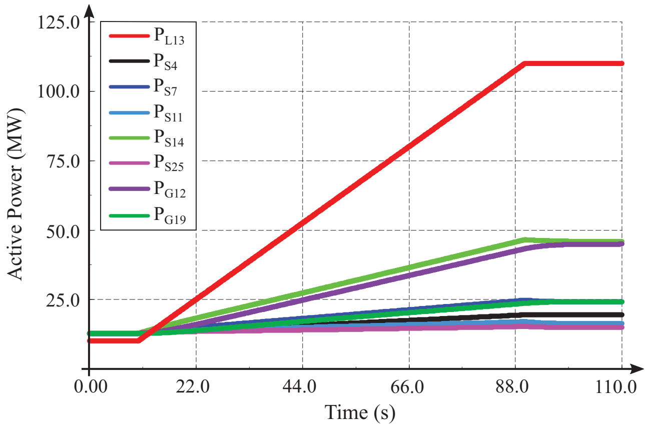

Fig. 10. Response of storage power plants and angle controlled conventional generators to increasing power demand in load 13

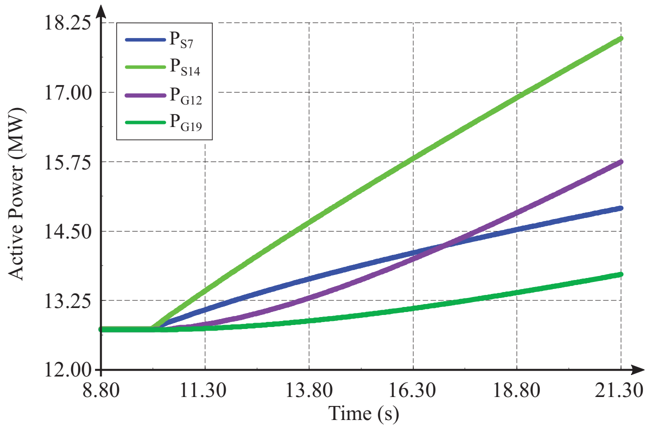

Fig. 11. Response speed of slack and angle controlled conventional generators

Hence, in the event of a disturbance, the load flow mainly emerges at that specific location, allowing the remote storage power plants to contribute little in terms of power supply. These trends are pronounced due to the use of a squared grid, as shown in Fig. 2. It would not be as easy to highlight the principles of power production during voltage angle control with such clarity in a grid with a non-uniform distribution of the line impedances.

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 plants. As indicated by the two linear power output lines, the storage power plants 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 plants 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 50% of their rated power. Operating below this threshold leads to higher 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 research findings prove that the rotating mass-free storage power plants 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 to 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. Investigations regarding the behavior of storage power plants under specific fault events, such as the loss of a transmission line, have exhibited improved results in terms of required re-dispatch power in the grid. Further analysis involving short circuit faults are currently underway. Additional research will also be required to estimate the total losses as well as the market compatibility of this novel system and hence complete a quantitative comparative study in relation to the current power system.

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