Available online at www.sciencedirect.com

ScienceDirect

IFAC PapersOnLine 52-4 (2019) 234–239

Improving Controllability of Conventional Power Plants using Voltage Angle Control

Prof. Dr.-Ing. Harald Weber *, **Nayeemuddin Ahmed** **

* *Electrical Energy Supply (EEV), University of Rostock, Rostock 18059, Germany (e-mail: harald.weber@uni-rostock.de)*
** *University of Rostock, (e-mail: nayeemuddin.ahmed@uni-rostock.de)*

Abstract: In the future, most of the fossil fuel based power plants of today will progressively be replaced by complete inertia-independent systems. Such systems, referred to as slack storage power plants, will consist of power electronic converters and storages in order to store power from renewable sources. However, some of the conventional thermal and hydroelectric power plants of today will remain in operation and act as base power plants in the power grid. 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 plants. All the control principles existing at present 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. 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. During the excessive power generation from renewables, the storage power plants can boost their power reserve. This allows the conventional power plants to continue operating within permissible thresholds. 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: controllability, nodal voltage angle control, renewables, storage, slack.

1. INTRODUCTION

One of the main challenges today is the increasing integration of intermittent renewable energy sources (RES), such as the sun and wind, into the power system. In Germany, with the large scale incorporation of wind energy, uncertainty due to forecast errors has increased, Weber et al. (2006). In addition, due to the rising presence and increased power generation from such renewables, at certain times the conventional power plants (CPPs) have to operate at a reduced power output, Huber et al. (2013). During these situations, the power supplied by such CPPs has to be drastically lowered and hence their controllability needs to be increased.

In the future, when the electrical power supply system will primarily be dependent on RES, a viable energy storage system would also be of paramount importance due to the stochastic nature of the source, Vazquez et al. (2010). Thus, to resolve these issues regarding electrical power supply and grid control, a new kind of "conventional" power plant is presented in this paper. Such a system, called the Storage Power Plant (SPP), is able to store the excess energy generated from RES in bulks for possible forecast errors and cold periods.

The SPPs do not possess any rotating masses and consist of converters and storage devices such as the battery and supercapacitor. Similar to wind turbines and solar panels, the SPPs are connected to the grid via power electronic converters and as a result do not have any inertia. However, in order to function effectively in the current electrical network, the SPP converter systems have to adapt to the rotating masses and respective frequency of the CPPs. This can be done by synthetically generating rotating inertia and primary reserve power. To achieve this, the converters have to measure the instantaneous active power at the connecting node so they can properly feed their angle-oriented regulating power into the grid. This way, these new converter systems can also function as power plants and can hence be integrated into the grid.

In the future, when the number of CPPs reduces significantly due to the lack of fossil fuels, the need for such power converters to adapt to rotating masses will diminish and frequency control may become obsolete. A new method of grid control can then be introduced, known as the nodal voltage angle control, Weber et al. (2018). The following sections of this paper highlight the advantages of such a method over the traditional frequency control.

2. THE NEW STORAGE POWER PLANT (SPP)

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.

Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2019.08.195

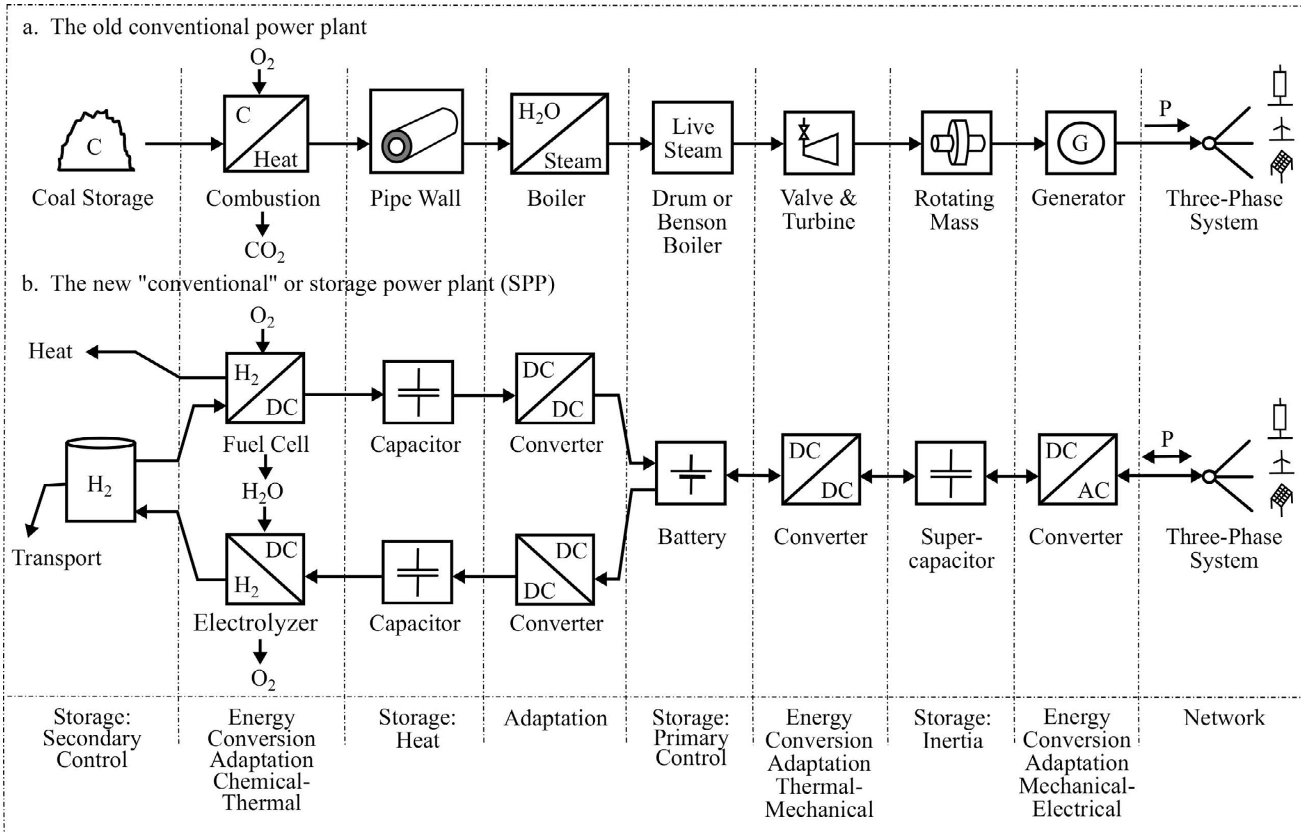

Fig. 1. Comparison between the (a) existing fossil fuel based and (b) new storage power plant (SPP)

- 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.

As of today, these tasks are being performed by CPPs, 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. If the power supply becomes completely converter-based in the future, then the SPPs 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 the new type of rotating mass-free SPP, which can work in grid-forming mode. Its mode of operation, with an example of a step increase in the active power requirement at the DC/AC converter, is explained as follows:

(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 output power. A capacitor is chosen for this purpose since it can immediately supply large magnitudes of power. As a result, the voltage of the supercapacitor decreases, which marks the amount of stored energy. These features are similar to that of the spinning reserve in CPPs 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 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 thermal 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 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 thermal 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 this is analogous to the heat stored on the pipe walls inside the boiler 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, to instantaneously respond and provide the necessary ancillary services autonomously. Contrary to current power plants, 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 sources or decrease in load demand, there is a shock-free transition from fuel cell to electrolyzer operation to store the excess energy. The corresponding converters adjust the voltage of each component, while the electrolyzer produces hydrogen of the required pressure which can also be used later for automobiles.

3. ANGLE REGULATED OPERATION OF CONVENTIONAL AND STORAGE POWER PLANTS

When the power supply system will mainly rely on SPPs, "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.

SPPs 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 per day. These features are present in the current CPPs 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 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 110 kV. 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. 7 is analyzed in this section. There are 11 power plants, 5 of which are slack SPPs, i.e. generators at terminals where the voltage magnitude ($|V|$) and angle (ϕ_u) are known. The other 6 are PV power plants with known active power (P) and voltage magnitude at the terminals. 4 out of these 6 are wind power plants, while the remaining 2 each represent a conventional hydroelectric (H_ϕ) and a steam (T_ϕ) power plant with an angle controlled governor. 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 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 dynamic RMS simulations are carried out in the software DIgSILENT PowerFactory. The SPPs 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 connected to a power measuring device. The required signals are passed to the angle controller as

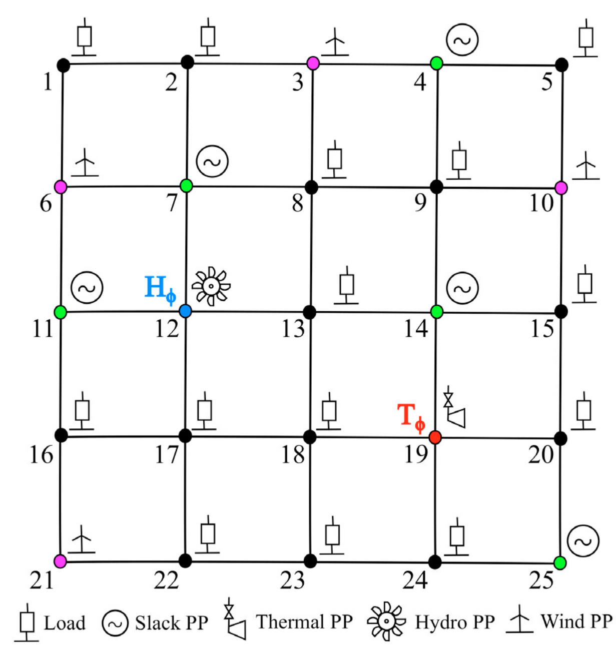

Fig. 2. 25 node example network

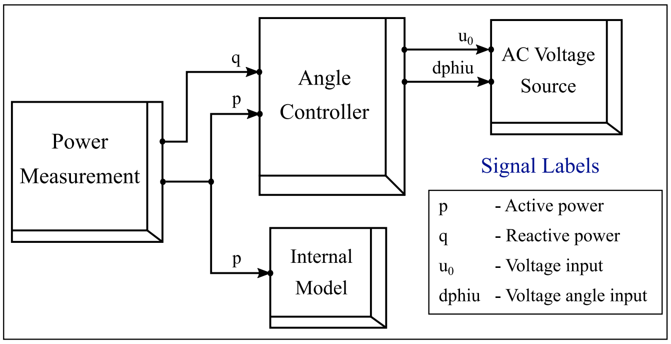

Fig. 3. Composite frame for the AC Voltage Source representing a SPP or wind power plant

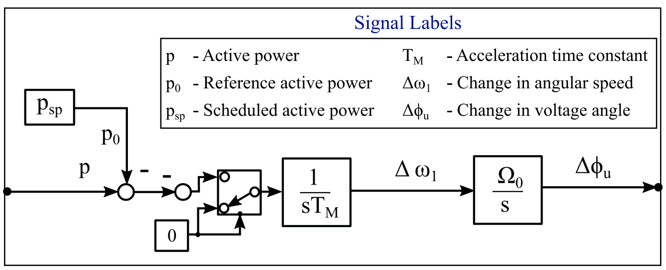

Fig. 4. Model definition for the angle controller of the SPP

well as the internal model containing the structure for the converters, supercapacitor, battery, fuel cell etc. The voltage magnitude and its angle obtained as the output of the controller are fed as inputs to the AC Voltage source. The wind power plants are also represented by a similar frame, but they do not have the internal model slot as shown in Fig. 3.

A simplified model for the angle controller of the slack SPPs and wind power plants is shown in Fig. 4. The switch is closed for wind power plants and open for the slacks. The opened position ensures that irrespective of the value 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 from the initial loadflow value throughout the course of the dynamic simulation. This will enable the slack node to keep its initial voltage angle.

The closed position of the switch for the wind power plants allows the angle of its voltage phasor to change. This causes the power plant to have a constant power output and thus function as a PV node. The reactive power signal q, its reference value is used to find the appropriate voltage magnitude u_0 for both slack SPPs and wind power plants. However, this model is not included in Fig. 4 since the reactive power results are not analyzed in this paper.

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

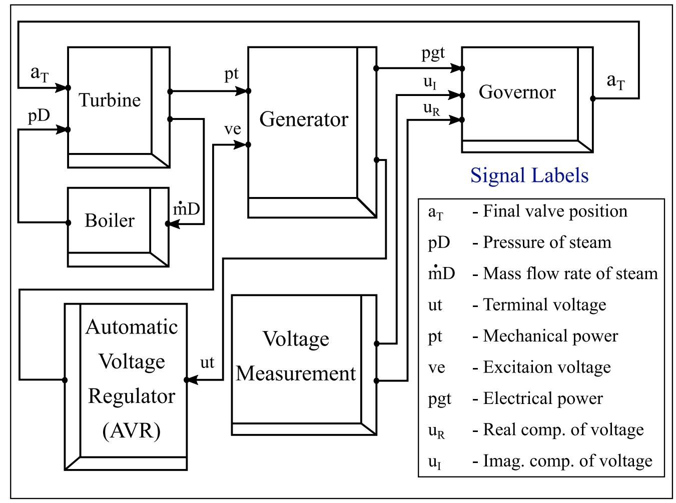

Fig. 5. Composite frame for the synchronous generator representing a thermal power plant governed by angle control

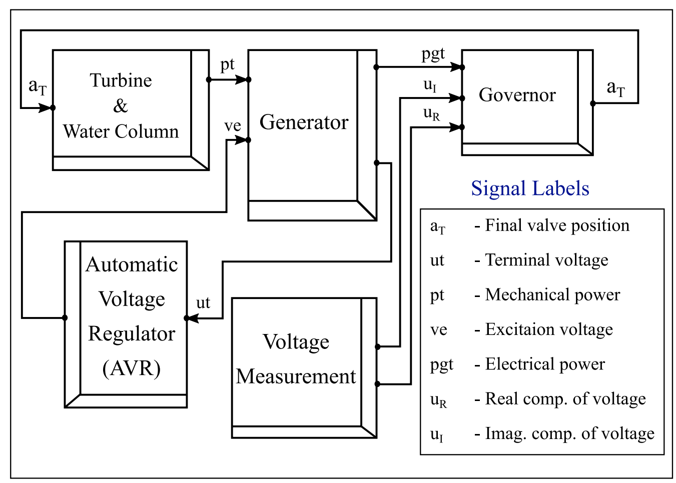

Fig. 6. Composite frame for the synchronous generator representing a hydroelectric power plant governed by angle control

information regarding the scheduled power flow is used to determine a new valve position which alters the rate of steam flow 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.

The composite frame for the conventional hydroelectric 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 hydroelectric power plant and the different turbine structures being used, Weber et al. (2002). 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 hydroelectric turbine and hence the electrical power output of the generator. Every component shown in the

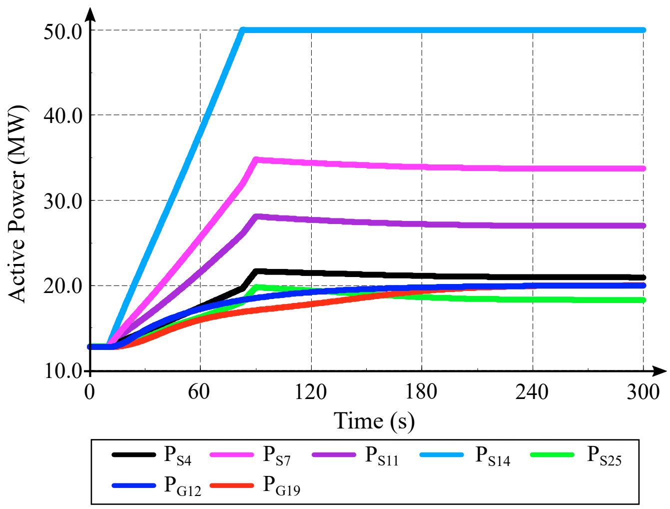

Fig. 7. Response of the SPPs and CPPs to increasing power demand in load 13

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.

In order to investigate the dynamic interaction between the four types of power plants, the following changes are then implemented in the network 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.
- The maximum power generation and storage limit for all SPPs is set at 50 MW and −50 MW respectively.
- The output of the CPPs is controlled to be between 10 MW and 20 MW, so they operate within 50% and 100% of their rated power.
- The power output of the wind power plants are kept constant at their initial value of 12.7 MW.

For this load flow calculation, all nodes with SPPs are treated as slack nodes, and their voltages are taken from the initial load flow with the single slack at node 25.

The reaction of all the SPPs and CPPs to the increased power demand at node 13 is shown in Fig. 7. The additional power supplied by each power plant depends on its electrical proximity to the central consumer. The slack SPP at the neighboring node 14 provides the highest increase in active power output and reaches its power limit at 50 MW. Once this happens, the four other slack generators in the system autonomously increase their rate of power generation to meet the increased demand. The slack at node 25 exhibits the lowest increase since it is the furthest angle controlled generator from load 13. Ideally, the hydro power plant at node 12 would have the second highest increase in power output, but in this case its maximum power output is limited to 20 MW. 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 demand increase of 100 MW. Such behavior of the angle controlled power plants is analogous to the combined effect of spinning reserve and primary control. Hence, in a network governed by nodal voltage angle control, the ancillary services are load flow oriented and are provided by the power plants close to the point of

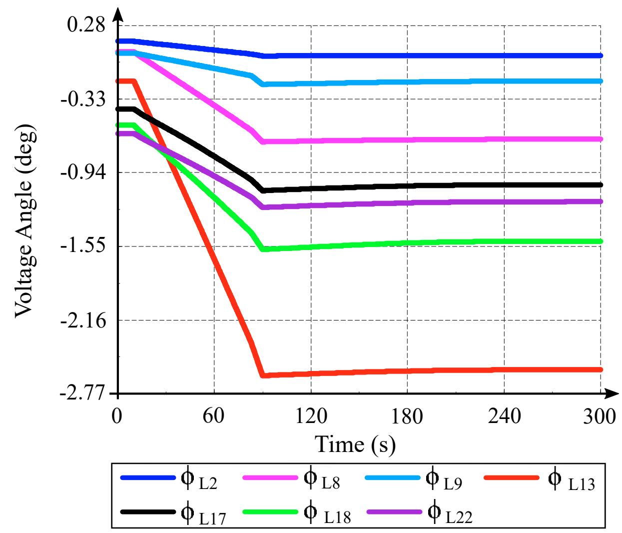

Fig. 8. Nodal voltage angles of some PQ loads

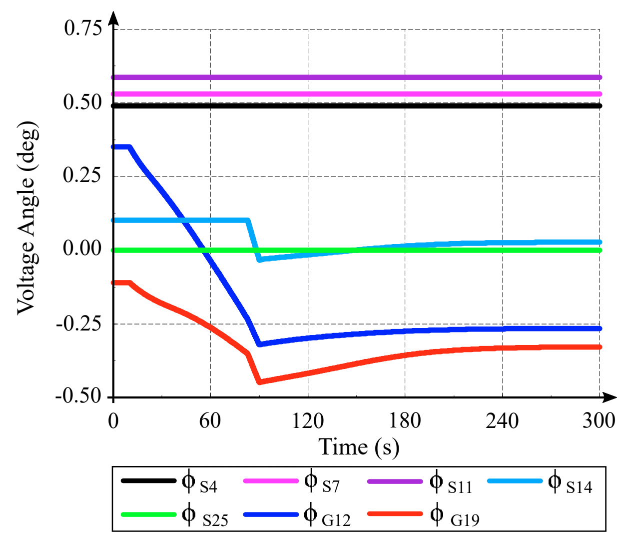

Fig. 9. Nodal voltage angles of all SPPs and CPPs

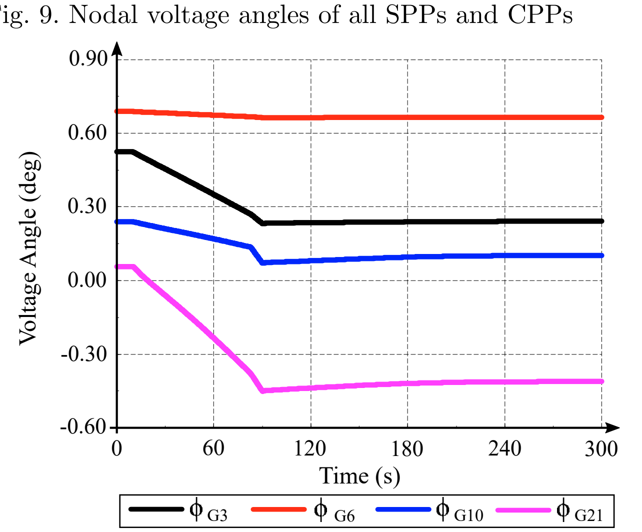

Fig. 10. Nodal voltage angles of all wind power generators

disturbance. As opposed to frequency control, this allows the power plants further away to remain undisturbed. 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

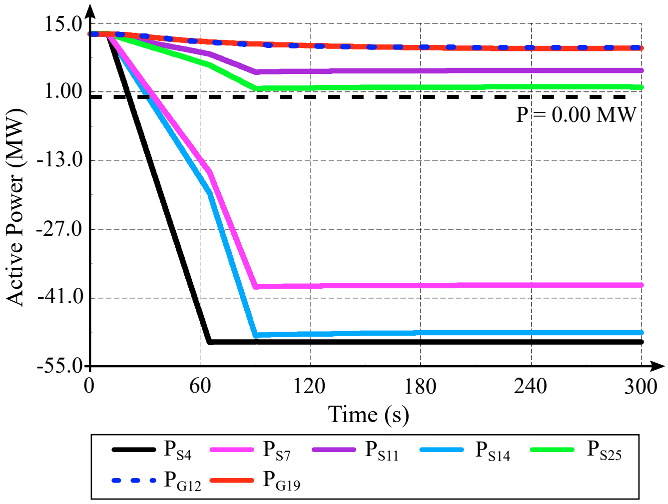

Fig. 11. Response of SPPs and CPPs to increasing wind power in nodes 3 and 10

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. 8 shows that the increase in power consumption at load 13, leads to 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 central node, for example node 2, are much smaller.

Fig. 9 exhibits that the grid-forming converters of SPPs are able to keep their voltage angles constant till they reach their generation limit. Upon reaching this threshold, the voltage angle of the slack is allowed to change in accordance to those of the nearby loads, allowing the slack to now function as a PV power plant. 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.

The two conventional generators in node 12 and 19, possessing angle controlled governors, are able to react to the voltage angle change of the load at node 13 and produce more power. If these generators did not have a maximum power production limit of 20 MW, then their voltage angles would eventually return to their initial value after reducing to a certain extent when the power demand is changing. However, since the output of these generators is controlled to always be within a specified range, the voltage angles can only return partially, ensuring that they remain positive in relation to the voltage angles of the nearby loads, as the system transitions to the steady state.

Fig. 10 illustrates that the voltage angles of the four wind power plants change in accordance to those of their nearby loads, to keep the angles constant between the two. As a result, these power plants continue to maintain a constant power output. The sharp decrease in the voltage angle for the generator in node 10 is a result of the slack at node 14 reaching its generation limit.

Next, the effect of an increase in renewable power generation on the 25 network is investigated. It is assumed that the kinetic energy of the wind from the north-east increases, causing the wind power plants in nodes 3 and 10 to ramp their power output from 12.7 MW to 112.7 MW between 10 s and 90 s. The power consumption by every load stays constant at 10 MW. Fig. 11 summarizes the reaction of the SPPs and CPPs to this change. Slack 4, the closest SPP to node 3 and 10, starts to store the maximum amount of power till it reaches its limit of −50 MW. When this threshold is reached, the other slacks autonomously start storing power at a higher rate with the ones closest to node 4 storing more. The CPPs reduce their power output as well, but this levels off at 10 MW ensuring that they operate at atleast 50% of their rated power. Working below this threshold leads to higher operating losses since the cost of keeping the power plant functional becomes too high compared to its generated output. Thus, with this type of control method, it is possible to always regulate the power output of the thermal or hydroelectric power plants within a permissible range.

4. CONCLUSION

The investigation results prove that the inertia independent SPPs with the modern high-performance grid control converter technology can function effectively with CPPs. Under voltage angle control, the power plants react autonomously to load and generation changes and satisfy the network demand. In addition, the performance of SPPs under this control method provides the opportunity of further integration of renewable sources and improves the controllability of CPPs. Investigations regarding the behavior of SPPs 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 is currently underway. However, additional research will be required to estimate the total losses as well as the market compatibility of this novel system and hence prepare a quantitative comparative study in relation to the current power system.

REFERENCES

M Huber, T Hamacher, C Ziems, and H Weber. Combining LP and MIP approaches to model the impacts of renewable energy generation on individual thermal power plant operation. In *2013 IEEE Power & Energy Society General Meeting*, pages 1–5. IEEE, 2013.

S Vazquez, S M Lukic, E Galvan, L G Franquelo, and J M Carrasco. Energy storage systems for transport and grid applications. *IEEE Transactions on Industrial Electronics*, 57(12):3881–3895, 2010.

H Weber, M Hladky, T Haase, S Spreng, and CN Moser. High quality modelling of hydro power plants for restoration studies. *IFAC Proceedings Volumes*, 35(1): 263–268, 2002.

H Weber, T Hamacher, and T Haase. Influence of wind energy on the power station park and the grid. *IFAC Proceedings Volumes*, 39(7):59–64, 2006.

H Weber, P Baskar, and N Ahmed. Nodal voltage angle control of power systems with renewable sources, storages and power electronic converters. In *2018 International Conference on Smart Energy Systems and Technologies (SEST)*, pages 1–6. IEEE, 2018.