Effects of Increasing Intermittent Generation on the frequency control of the European Power System

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Abstract: With increasing the intermitting generation such as wind power (WP) and photovoltaic (PV) in the European power system, the conventional power plants online will be replaced by WP and PV. Thus, the sources of conventional reserve available to the system will be reduced and fewer conventional plants will be available online to share the regulation burden. Reserve management by conventional plants will be difficult, especially in isolated power systems, which have no interconnection and limited capability of power regulation. The power system inertia will be reduced, greater rates of frequency change will be observed during system contingencies and conventional prime movers will have less time to react in order to keep the frequency stable. Therefore, this paper focuses on the effects of increasing intermitting generation on the frequency control of the European power system using different scenarios of the intermittent generation after occurrence of abrupt variations in generation and load. The model was created using SIMULINK/MATLAB software.

Keywords: primary energy, wind, frequency control, renewable energy sources.

1. INTRODUCTION

In order to achieve the goal of the European Union to cover 20% of the primary energy consumption by renewable energy sources until 2020, the feed-in of renewable electricity generation must be significantly raised in comparison to the contemporary level. For the German case, this implicates a rise of renewable share of electricity generation to 30% by 2020. The main part of the installed and forecasted renewable generation depends on intermitting energy sources such as wind and sun. The integration of this increasing share of intermitting generation while maintaining the present security level of supply confronts the existing power system with a big challenge.

The potential of renewable energy sources (RES) is enormous as they can in principle meet many times the world's energy demand. Renewable energy sources such as biomass, wind, solar, hydropower, and geothermal can provide sustainable energy services, based on the use of routinely available, indigenous resources. A transition to renewable-based energy systems is looking increasingly likely as the costs of solar and wind power systems have dropped substantially in the past 30 years, and continue to decline, while the price of oil and gas continue to fluctuate. In fact, fossil fuel and renewable energy prices, social and environmental costs are heading in opposite directions. Furthermore, the economic and policy mechanisms needed to support the widespread dissemination and sustainable markets for renewable energy systems have also rapidly evolved. It is becoming clear that future growth in the energy sector is primarily in the new regime of renewable, and to some extent natural gas-based systems, and not in conventional oil and coal sources. Financial markets are awakening to the future growth potential of renewable and other new energy technologies, and this is a likely harbinger of the economic reality of truly competitive renewable energy systems.

RES currently supply somewhere between 15% and 20% of world's total energy demand. A number of scenario studies have investigated the potential contribution of renewable to global energy supplies, indicating that in the second half of the 21st century their contribution might range from the present figure of nearly 20% to more than 50% with the right policies in place.

The situation in Europe differs from country to country. Circumstances may also differ between synchronous interconnected systems and island systems. The capacity targets and the future portfolio of RES depend on the national situation. Nevertheless, the biggest growth potential is for wind energy. The expectations of the European Wind Energy Association show an increase from 28.5 GW in 2003 to 180 GW in 2020. Due to different support schemes for RES restrictions in licensing and a limited number of suitable locations, this capacity tends to focus on very few regions in Europe. However, new wind farms will normally be built far away from the main load centers. New overhead lines will therefore be necessary to transport the electricity to where it is consumed. These investments are exclusively or at least mainly driven by the new RES generation sites. The intermittent contributions from wind power must be balanced with other backup generation capacity located elsewhere. This adds to the requirements for grid reinforcements. The licensing procedures for new lines are lasting several years, some even more than 10 years. A delay in grid extension will result in a delay of RES investments because wind farms cannot earn an adequate return on investment without an adequate grid connection. New lines are therefore critical for the success of new RES. Moreover, this new infrastructure

could be a significant investment. There is not yet an European-wide harmonized rule about who should pay for it. The legal framework and administrative procedures have to be set properly to speed up the licensing of grid infrastructure. As countermeasures, suitable European-wide harmonized grid codes for new wind farms and other RES defining their electrical behavior in critical grid situations are needed in all countries expanding their share of RES. Existing wind farms not fulfilling the actual grid code requirements must be upgraded or replaced (i.e. the electrical behavior of wind turbines in case of grid faults).

2. OVERVIEW OF THE EUROPEAN SYSTEM

In practice, a large interconnected power system is always divided into various "control zones" or "areas", corresponding to countries as shown in Fig. 1. For simplified simulation studies, a system with two areas (German system and the rest of the European system) can be represented by

two single bus systems with a tie line between them. This is depicted in Fig. 2. In order to adapt our dynamic frequency model accordingly, the power exchange $P_{exc,12}$ over the tie line between area 1 (German system) and area 2 (rest of the EU system) has to be modelled. This is given by equation 1 and the linearizing about an initial operating point represented by $\delta_1 = \delta_{Ger,0}$ and $\delta_2 = \delta_{EU,0}$, then we have the equation 2, where $P_{exc,12}$ is the exchange power on the tie line from area 1 to area 2, X is the equivalent reactance of the tie line, U_1 and U_2 are the voltages at tie bus of area 1 and area 2, δ_1 and δ_2 are the angles of area 1 and area 2 and T is the synchronizing torque coefficient.

$$P_{exc,12} = \frac{U_1 U_2}{X} \sin(\delta_1 - \delta_2) \tag{1}$$

$$\Delta P_{Ger,EU} = T \Delta\delta_{Ger,EU} = \frac{U_1 U_2}{X} \cos(\delta_{Ger,0} - \delta_{EU,0})(\Delta\delta_{Ger} - \Delta\delta_{EU}) \tag{2}$$
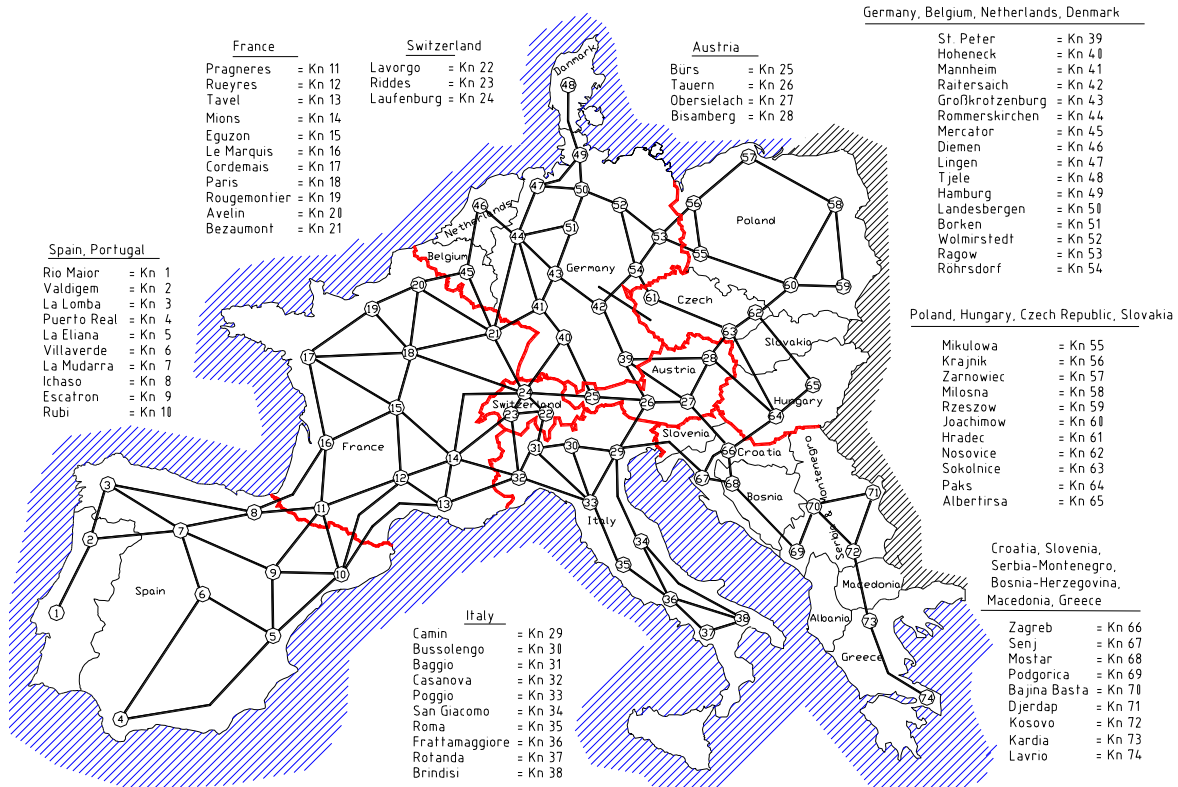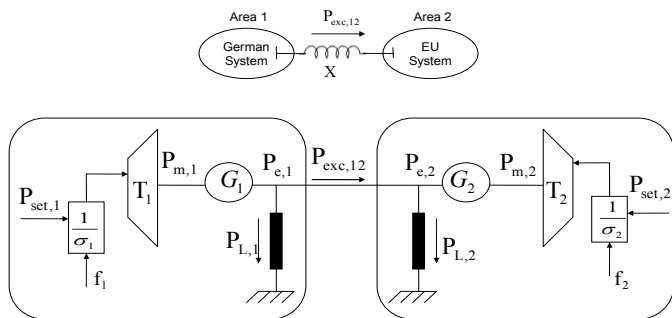

Fig. 1 .Simplified model of the EU system

Fig. 2. Simplified representation of a power system with two areas

By using this model, the block diagram of the power system can be extended as shown in Fig. 3. The block diagram representations of the system with each area represented by equivalent inertia (or the acceleration time constant T_N) in seconds, load-damping constant (D) and all power plants in German system are modelled in detail with their primary controllers and loads of Germany. Also the rest of Europe (e.g. France, Italy, Spain…etc.) are modelled with their primary controllers and loads for each country. Any model consists of separate models of power controller, governor and turbine system. The tie-line is represented by the synchronizing torque coefficient T. A positive $\Delta P_{Ger,EU}$ represents an increase in power transfer from area 1 to area 2.

This in effect is equivalent to increasing the load of area 1 and decreasing the load of area 2; therefore, feedback of $\Delta P_{Ger, EU}$ has a negative sign for area 1 and a positive sign of area 2. In such cases, a joint reaction of primary control of all interconnected systems is foreseen in order to re-establish the balance between generation and consumption. The result will be achieved at a frequency differing from its set-point value by Δf_{ss} and the power interchanges on tie lines will be different from the scheduled values.
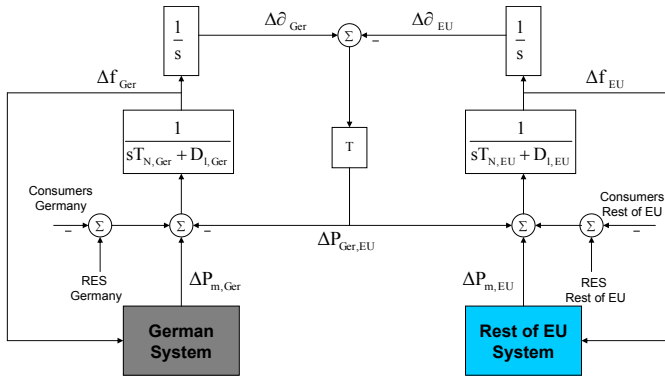

Fig. 3. Two-area dynamic model including tie-line flows with only primary control

The steady-state frequency deviation is the same for the two areas and it is calculated by equation 3, where $\Delta_{PL, Ger}$ and $\Delta_{PL, EU}$ are the step change in load of German and the rest of EU systems respectively, $P_{n, Ger}$ and $P_{n, EU}$ are the rated power of German and the rest of EU systems, $P_{n, all}$ is the rated power of both German and the rest of EU systems, $\sigma_{eq, Ger}$ and $\sigma_{eq, EU}$ are the equivalent of the speed droop of German and the rest of EU systems, D_{Ger} and D_{EU} are the self-regulation of the load of German and the rest of EU systems respectively.

$$\Delta f_{ss} = \Delta f_{ss, Ger} = \Delta f_{ss, EU} = \frac{-\Delta P_{L,Ger} * \frac{P_{n,Ger}}{P_{n,all}} - \Delta P_{L,EU} * \frac{P_{n,EU}}{P_{n,all}}}{(\frac{1}{\sigma_{eq,Ger}} + D_{Ger}) * \frac{P_{n,Ger}}{P_{n,all}} + (\frac{1}{\sigma_{eq,EU}} + D_{EU}) * \frac{P_{n,EU}}{P_{n,all}}} \quad (3)$$

The acceleration time constant (T_N) in seconds, which is calculated by the inertia of the generators and motors, commonly states how much time it takes from standstill to accelerate an inertia that is driven by its nominal torque or power until the nominal rotational speed is reached. Within the electrical energy system the inertia is of vital importance, since only the inertia is able to stabilize the network frequency at an acceptable value in the first moment after a disturbance of the power balance. Normally wind turbines are connected to the system via frequency inverters and photovoltaic systems are always connected via DC/AC converters, so they are mechanically and electrically decoupled from the system and cannot increase the acceleration time constant. Therefore, it has to be lined out that the acceleration time constant is reduced, if more renewable energy sources (WP and PV) are connected to the system when at the same time the number of conventional power plant generators with masses are displaced by these intermittent generators as shown in the Fig. 4 while the total nominal power value of the whole system remains constant.
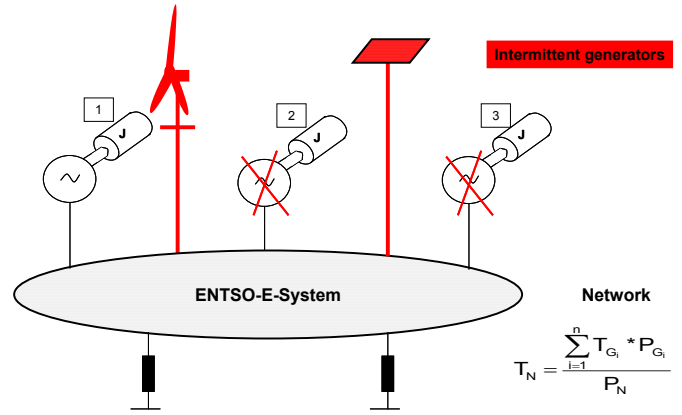

Fig. 4 . European System

The acceleration time constant can be calculated by equations (4) and (5) where T_{Gi} is the acceleration time constant for individual units in seconds, P_{Gi} is the rated power of an individual Generator in MW, P_{REF} is the intermittent rated power in MW, J is the moment of inertia of the rotor mass in kg-m^2 and Ω_N is the angular velocity of the mass J in radians per second.

$$T_N = \sum_{i=1}^{n} T_{G_i} . P_{G_i} / \sum_{i=1}^{n} (P_{G_i} + P_{RES}) \quad (4)$$

and $T_{G_i} = J_i . \Omega_N^2 / P_{G_i}$ (5)

3. CASE STUDY FOR THE EUROPEAN POWER SYSTEM

Three scenarios are investigated in combination with high and low load and Fig. 5 shows the case study for the European power system. The system inertia (or the acceleration time constant of the system) in both German and the rest of the EU systems are decreased but not the same ratio and then the overall inertia will be reduced in several steps due to increased feed-in from wind and photovoltaic systems. In these scenarios, the inadvertent exchange power flows due to the primary control are of special interest. The total amount of primary control reserve in the whole EU system is 3 GW. Power plants that provide the primary control power will be changed to different types of power plants (e.g. gas turbines, thermal plants, hydro plants and nuclear plants) and the power plant types have different transfer functions and time constants and therefore influence the dynamic behavior. Currently in German system, the hydropower plants do not contribute to the primary reserve. After that, we assume that the hydropower plants may contribute to the primary reserve in the future due to the shut down the nuclear power plants and some of thermal units in Germany by 2020.
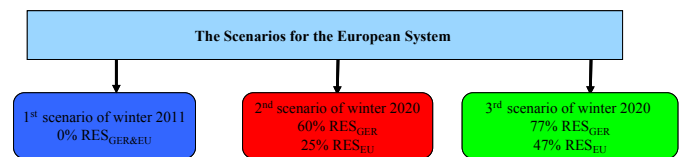

Fig. 5. The case study for the European power system

3.1 First scenario of winter 2011 (0% WP&PV)

Fig. 6 shows the first scenario of winter 2011 with no intermittent renewable energy in operation in both German and the rest of the European systems. The upper pie charts show the power plants in operation for both German system (left) and the EU system (right). The lower pie charts show the contribution of the primary control reserve for both German system (left) and the EU system (right) and allocated to hard coal power plants, lignite power plants, gas power plants and combined cycle gas power plants in addition to the hydro power plants in the rest of the European system.
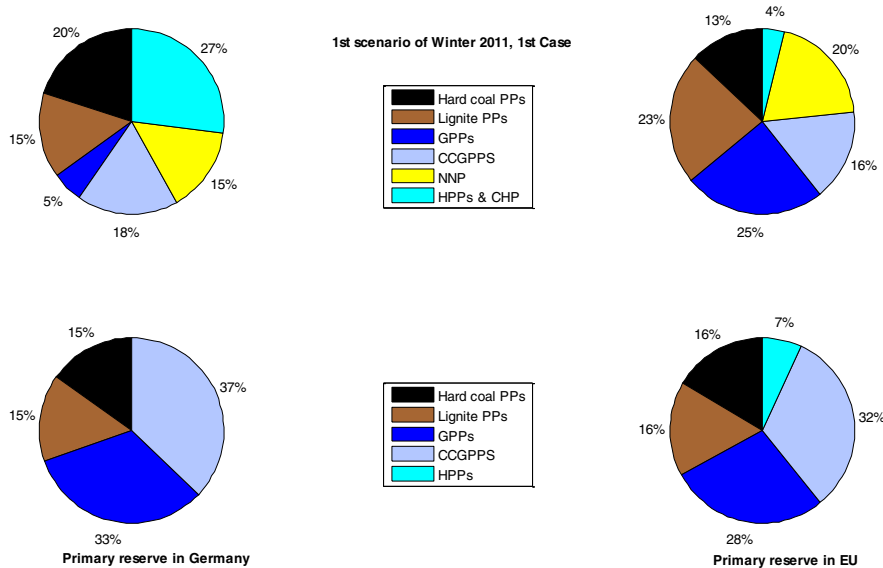

Fig. 6. First scenario of winter 2011

3.2 Second scenario of winter 2020

Fig. 7 shows the second scenario of winter 2020. In this scenario, the RES for German system is increased to 60% and for the rest of the European system is increased to 25%. The upper pie charts show the power plants in operation for both German system (left) and the EU system (right). In German system, the gas turbines, some of thermal and some of nuclear power plants are shut down and replaced by wind and photovoltaic power plants (60%). In the rest of EU system, some of gas turbines and some of hard coal power plants are shut down and replaced by wind and photovoltaic power plants (25%). The lower pie charts show the contribution of the primary control reserve for both German system (left) and EU system (right). The contribution of primary control reserve for the German system is allocated to hard coal power plants, lignite power plants, combined cycle gas power plants and hydro power plants. For the rest of EU system, the primary control reserve is allocated to hard coal power plants, lignite power plants, combined cycle gas power plants, nuclear power plants and hydro power plants.
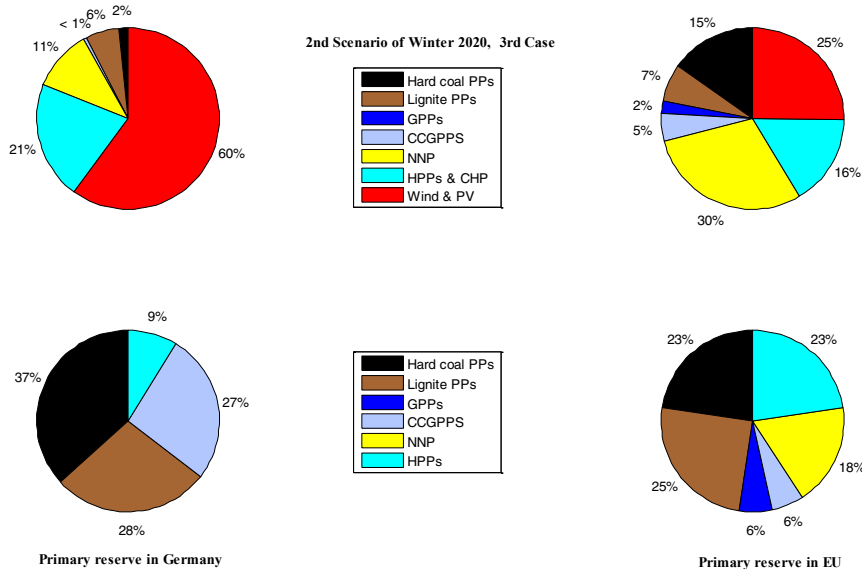

Fig. 7. The second scenario of winter 2020

According to the second scenario of winter 2020, Fig. 8 shows the comparison of the installed wind power capacity in MW in the EU-27 countries. It can be seen that Germany has the largest contribution of wind power with a value of approximately 44 GW.
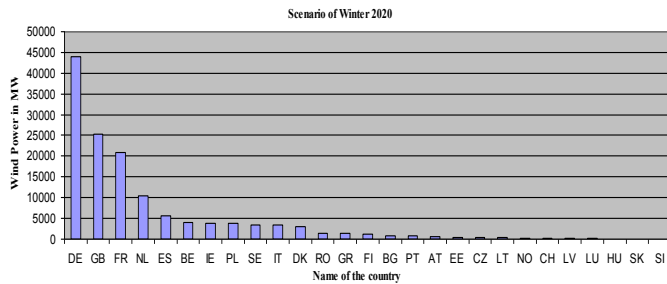

Fig. 8. Predicted total installed wind capacity (in MW) in the EU-27 countries

3.3 Third scenario of winter 2020

Fig. 9 shows the third scenario, winter 2020. In this scenario, the intermittent renewable energy is increasing for German system and for the rest of the European system to 77% and 47% respectively. The upper pie charts show the power plants in operation for both German system (left) and the EU system (right). In German system, the gas turbines, some of thermal and some of nuclear power plants are shut down and replaced by wind and photovoltaic power plants (77%). As for the rest of EU system, some of gas turbines and some of thermal power plants are shut down and replaced by wind and photovoltaic power plants (47%). The lower pie charts show the contribution of the primary control reserve for both German system (left) and EU system (right). The contribution of primary control reserve for the German system is allocated to hard coal power plants, lignite power plants, combined cycle gas power plants and hydro power plants. For the rest of EU system, the primary control reserve is allocated to hard coal power plants, lignite power plants, combined cycle gas power plants, nuclear power plants and hydro power plants.
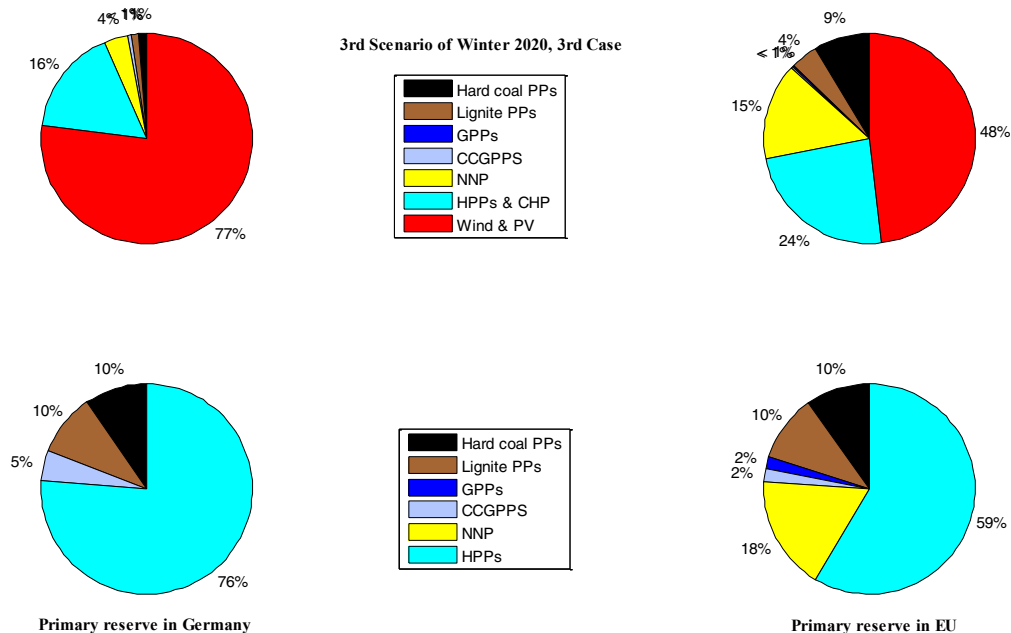

Fig. 9. The third scenario of winter 2020

4. SIMULATION RESULTS

Fig. 10 shows the frequency deviation and the exchange power between German and rest of EU systems for the first scenario (blue line), second scenario (red line) and third scenario (green line) due to 3 GW generation loss in German system. In the first scenario, no intermittent renewable energy increases in both German and EU systems, second scenario the intermittent renewable energy increases in German and rest of EU systems to 60% and 25% respectively and for the third scenario the intermittent renewable energy increases in German and rest of EU systems to 77% and 48% respectively. For the first scenario, no change in the inertia in both German ($T_{N, Ger}$) and EU systems ($T_{N, EU}$) while for the second and third scenarios, the inertia will decrease to 3.6s and 1.85s respectively for German system and decrease to 6.93s and 4.86 respectively for the rest of EU system.
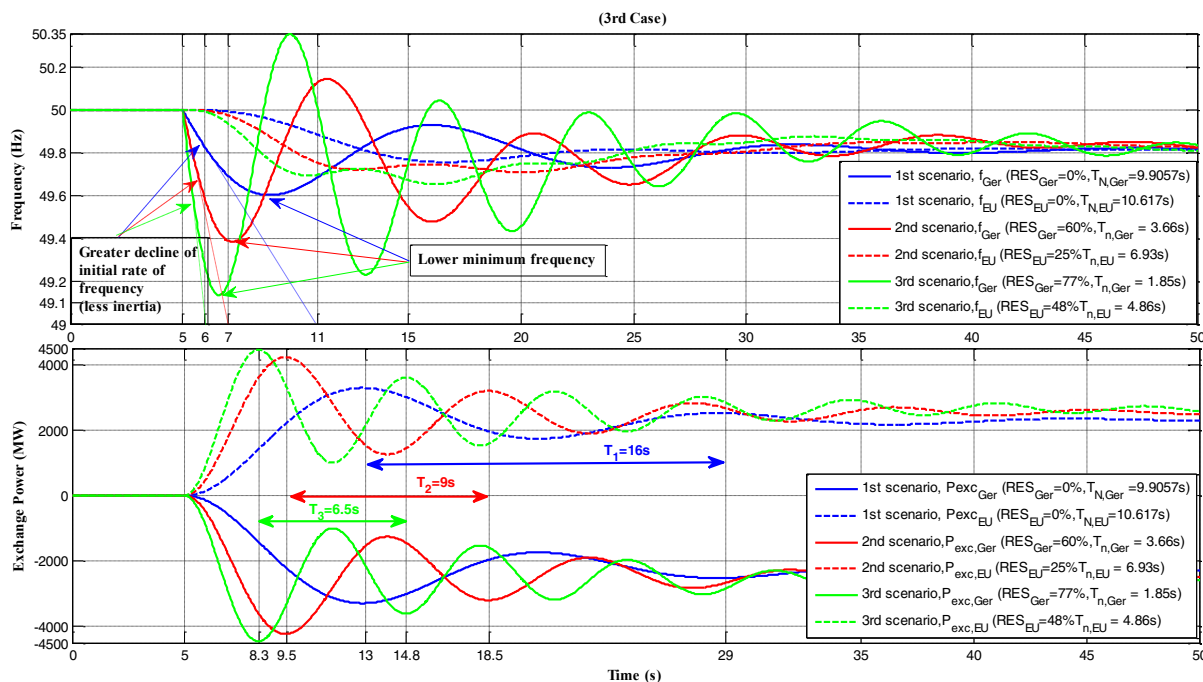
Fig. 10 Frequency and power exchange between German and EU systems for scenarios 1, 2 and 3 of interconnected model

As results, for the first scenario the frequency deviation reached to -390 mHz and for the second scenario the frequency deviation reached deeper to -615 mHz with more oscillation occurring compared to the first scenario and for third scenario the frequency deviation reached deeper more and less than -800 mHz and more oscillation occurs due to decrease in the system inertia and due to the increase of the contribution of HPPs and NPPs in to the primary control reserve of the system. Also it can be seen that the exchange power between German and EU systems increases with oscillation when increasing the renewable energy sources and with more oscillations due to the increase of the contribution of HPPs and NPPs to the primary control reserve of the system.

5. CONCLUSIONS

Due to the shut down of some conventional power plants and replacement by wind and photovoltaic power producers using different scenarios, the existing inertia mass time constant (T_N) in the grid decreases (from 10s to 2s). This will show a greater decline of the initial rate of frequency (from -66.6 mHz/s to -850 mHz/s), deeper frequency deviations (from -390 mHz to -900 mHz) and oscillations (from 80 to 160 mHz) with shorter period (from 16s to 6.5s) after a 3-GW-disturbance. Also, the maximum exchange power between Germany and the neighbours increases dynamically from 3300 to 4000 MW. In this situation the power system is influenced seriously, because consumers and coupling lines can be tripped simultaneously what can result in islanding of the system. Also the higher rate of primary control oscillation frequency will reduce lifetime of the involved power plants. Finally, in case of high rate of hydro power plants in the system during particular time periods because of the so called counteraction of the plants (Hydraulic turbines have a peculiar response due to water inertia: a change in gate position produces an initial turbine power change which is opposite to that sought) also the system can become unstable caused by primary control.

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