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An Open-Source Educational Toolbox for Power System Frequency Control Tuning and Optimization

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***Abstract*—This paper presents an open-source educational tool for power and control engineering students to practice frequency control and test tunings and control strategies. The disturbance scenarios are realistic and automatically generated by the tool. This feature facilitates statistical analyses of the behaviour of the system. The paper shows simulation results with a common disturbance scenario and with two more severe cases.**

I. Introduction

The frequency variation of a power system is a direct result of the balance between power generation and consumption. This means that if generation and consumption are not made to match, the excess (deficiency) of energy will be translated into an increase (decrease) of the system frequency, f.

The sensitivity of electrical equipment to frequency deviations is high and the consequences severe - even deviations smaller than 1% can lead to damage, degradation of performance and trips of loads and generators [1].

The past decade has seen a significant increase in the number of such frequency incidents which, in part, can be attributed to the increasing penetration of renewable energies. Because the production of renewable generators cannot be precisely scheduled, the overall system generation loses controllability, and load-generation imbalances are more likely to happen. An obvious example is the Nordic system where roughly a two-fold increase in wind power installed capacity was accompanied by a two-fold increase in the number of frequency incidents [2], [3], *i.e.* $f < 49.9Hz$ or $f > 50.1Hz$.

Commercial power systems software offers detailed representation of electrical equipment but may be unavailable to power and control engineering students.

This paper presents an educational software toolbox which is available online [4]. This long-term dynamic simulation model comprises several features of a realistic frequency control system, conditioned to constant voltage, single control area and all machines connected to the same bus. The constant voltage condition is a valid assumption when effective voltage control is in place. The necessary modifications to reproduce a N-control area power system are discussed in section 6. The control strategy implemented follows the current industrial practice. In addition, the tool is able to generate realistic sequences of power imbalances, provided a worst-case imbalance characteristic which can be defined by the user. This is a complement to the academic step disturbance, against which these systems are mostly tuned [5], [6].

The tool is aimed at power and control engineering students, to facilitate the learning of frequency control and testing of different control tunings and strategies. An example of using the model proposed by this tool for frequency control design is given in [7] with model predictive control.

The paper is organized as follows. Section II explains the current practice in power systems frequency control. The educational software toolbox is presented in Sections III and IV; Section III focuses on modelling whereas section IV describes the imbalance functions. Section V shows results obtained with the tool. Section VI concludes the paper.

II. Power System Frequency Control

Frequency control is usually provided by generating units which can modulate their generated power. In current industrial practice, these reserves can be used in three different services. The classification adopted by this paper is the one proposed by the European Network of Transmission System Operators for Electricity (ENTSO-E) [8], *i.e.* Frequency Containment Reserves (FCR), Frequency Restoration Reserves (FRR) and Replacement Reserves (RR). These services correspond roughly to the terminology of primary, secondary and tertiary services used in continental Europe [9]. The commission and decommission of the reserves in each service is controlled by separate control loops, as depicted in Fig.1. This simplified block diagram shows the three distinct sets of power reserve units and the three dedicated control loops with their corresponding parameters.

The FCR service is time-critical and must be able to stabilize frequency within tens of seconds. Only generating units that can respond fast enough to frequency variations can participate to this service. Historically in the Nordic network, this service has been almost exclusively provided by hydro power generators. The control of these units is provided by the autonomous proportional action of the speed governor, which is represented by the speed-droop characteristic (R) [1].

Because of the proportional law, the FCR service is not capable of restoring the frequency to its nominal value, so the FRR service takes over the former to guarantee frequency restoration. This service is not as time-critical as stabilizing frequency excursions, so units which activate within tens of

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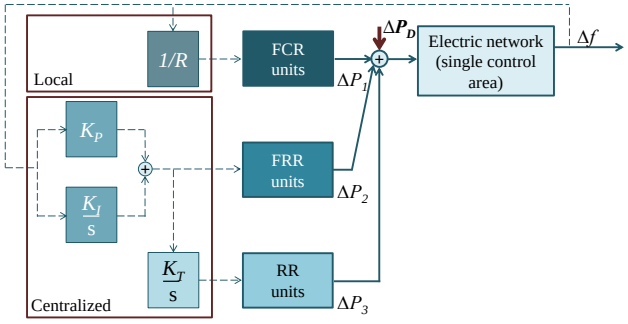


Fig. 1: Single area power system frequency control.

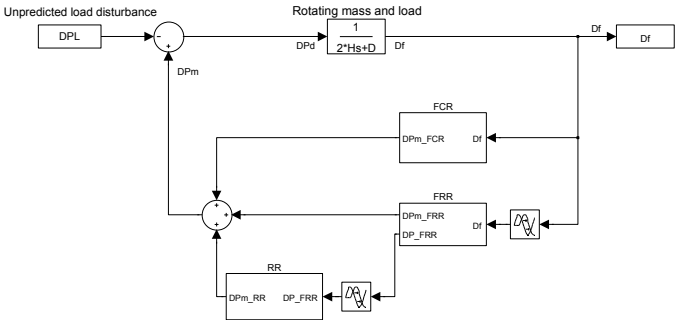


Fig. 2: Simulink model in FRECOL: first layer

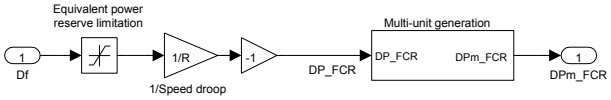


Fig. 3: Under mask of FCR block.

seconds to minutes can participate. This service is typically provided by thermal power generators and recently there have been suggestions on how to include industrial loads [10]. The control of FRR units is provided by a centralized controller, which responds to a regulation signal, which for a single control area is the frequency deviation. Proportional-integral (PI) controller is the widely used mechanism for this service, and the two controller parameters, proportional gain (K_P) and integral gain (K_I), are commonly tuned with heuristics and trial-and-error approaches [1].

For longer time horizons, the RR service substitutes the FRR, which has limited energy reserves and is more expensive. Units participating to the RR service are usually asked to respond within several minutes and have to sustain their service for longer periods. This service is provided by thermal generators as well as some controllable loads. The control of these units is often manual; after some time of the secondary reserves being activated, an operator in the system control centre issues an order to activate the replacement reserves.

III. Representation of Power System and Frequency Control in FRECOL

FRECOL (Frequency REserve Control Open-source Library) is a MATLAB Simulink toolbox which is available online [4]. Its purpose is to serve as an open-source educational tool for power and control engineering students to practice frequency control and test different tunings and control strategies against realistic disturbance scenarios.

This section presents the models of the power system and frequency control implemented, using the notation of the tool.

FRECOL represents the power system as a one control area and assumes constant voltage and machines connected to a single bus. Fig. 2 shows the first layer of the Simulink model. The dynamic frequency response of the power system to power imbalances is modelled by the first-order linearized relation shown in the block labelled as Rotating mass and load. Parameters H and D in that equation account for the inertia of the rotating masses and the self regulation of the load, respectively. This is a valid assumption for frequency control in the presence of load imbalance since the dynamics affecting frequency response are relatively slow [1].

The three frequency control services are implemented in the blocks labelled FCR, FRR and RR in Fig. 2.

The details of the FCR block are shown in Fig. 3. The gain blocks model the proportional control action of FCR units through the speed-droop characteristic ($1/R$). The power reserve commitment of the generating units should be limited to a predefined amount. This power reserve limitation is implemented in the saturation block in Fig. 3 as the equivalent frequency limitation B; this parameter is specified by grid codes and indicates that at $\pm B$ FCRs should be fully activated.

The generating units in FCR are modelled as hydro units according to [11]. In this case, the dynamics of the governor is represented by a one-zero, two-pole equation and the turbine by a one-zero, one-pole equation (1).

$$G_{FCR} = \underbrace{\frac{T_3 \cdot s + 1}{(T_2 \cdot s + 1)(T_4 \cdot s + 1)}}_{\text{Governor}} \cdot \underbrace{\frac{-T_w \cdot s + 1}{T_w/2 \cdot s + 1}}_{\text{Turbine}} \quad (1)$$

where T_2, T_3 and T_4 are governor time constants and T_w is the water time constant of hydro turbines.

Frequency control services are usually provided by several units in parallel. As shown in Fig. 4, the model of the FCR service includes multiple generating units, which the user can easily remove or add to. Each unit can have distinct time constants because these are implemented as vectors in FRECOL. The participation of unit i to the FCR service is implemented in the i^{th} gain block in Fig. 4 as $\frac{FCR(i)}{(B/R)}$, *i.e.* the predefined power reserve of unit i relative to the total power reserve of the service. This approach is used instead of actual participation factors to allow for the possibility of the units not being capable of generating as much power as demanded by the controller, *i.e.* $\sum FCR(i) < (B/R)$. In this case, the programme returns warning.

The FRR control loop is implemented with a PI control law as shown in Fig. 5. The proportional and integral gains are denoted as KP_FRR and KI_FRR in the Simulink model.

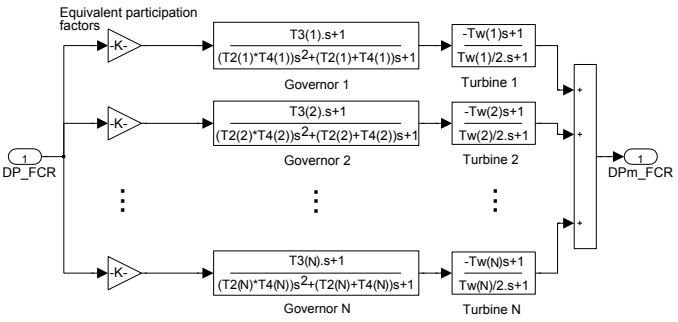


Fig. 4: FCR generation, under *Multi-unit generation* mask.

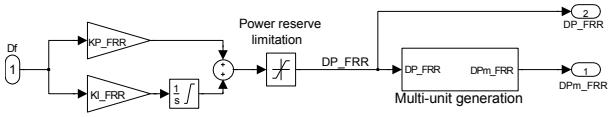


Fig. 5: Under mask of FRR block.

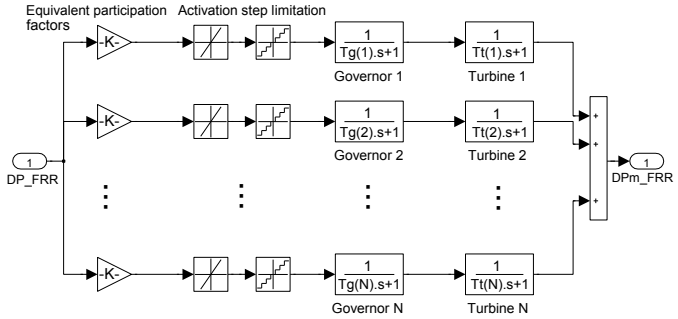


Fig. 6: FRR generation, under *Multi-unit generation* mask.

The total power reserve of this service is limited to FRRP in the saturation block of Fig. 5. Furthermore, to avoid winding-up of the integral control action, the integrator block for the integral action is also limited to FRRP.

Generation in FRR is modelled by generic thermal units according to [1]. In this case, the dynamics of governor and turbine can be represented by the first-order model (2).

$$G_{FRR} = \underbrace{\frac{1}{T_g \cdot s + 1}}_{\text{Governor}} \cdot \underbrace{\frac{1}{T_t \cdot s + 1}}_{\text{Turbine}} \tag{2}$$

where T_g and T_t are the governor and turbine time constants.

As with FCR, the participation of each unit is also implemented in the gain blocks of Fig. 6 as $\frac{FRR(i)}{FRRP}$. A warning message is issued if $\sum FRR(i) < FRRP$.

European guidelines suggest thermal units should be activated with a ramp limited signal [12], imposed by the rate limiter blocks in Fig. 6. The following quantizer blocks model the FRR cycle time and the coarseness of the unit activation.

An additional physical constraint of the FRR service featured in the model is the time delay shown in Fig. 2 before the FRR block. This block models the communication delay of the measured frequency between the operating unit and the controller localized in the control center. In a multi-area system this delay also models the time to obtain power imbalances from the SCADA/EMS system.

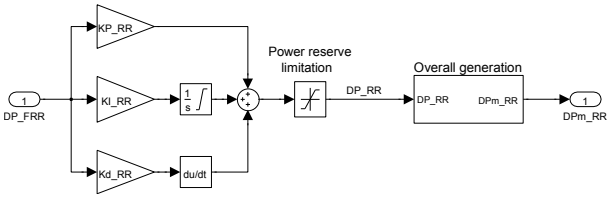


Fig. 7: Under mask of RR block.

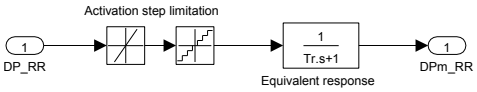


Fig. 8: RR generation, under *Overall generation* mask.

Block RR in Fig. 2 provides for the decommitment of the FRR units, rather than modelling faithfully the RR service. Therefore, the manual control of the RR units by the operator is mimicked as an integral action on the FRR control signal, with equivalent integral gain KI_RR. The total power reserve limit of this service, RRP, is likewise implemented in the saturation and integrator blocks. This is shown in Fig. 7, where proportional and derivative control actions can also be seen. By default, the tool has the gains in these actions set to zero, but the user may change them to test alternative representations of the manual actions of the operator. The delay before block RR in Fig. 2 simulates the overall delay of measurement, communication, state estimation and operator action.

The overall dynamics of RR units is represented as a first-order response with time constant Tr, as shown in Fig. 8. As with the FRR service, limits to activation rate of the units, cycle time and resolution of the activation are modelled by the rate limiter and quantizer blocks.

IV. Power imbalance functions

Block DPL in Fig. 2 injects power imbalances in the system. These can either be given by the user or FRECOL can generate random imbalances constrained to a worst-case area.

With the constrained random disturbance, the imbalance varies continuously with magnitudes of random value but restricted to a worst-case curve, as represented in Fig. 9 (left). At any time *n*, the future imbalance scenario is constrained to the intersection of similar such curves, centered on the actual imbalances occured at all the previous time instants. For simplicity, Fig.9 (right) illustrates this concept at discrete time instants. The worst-case curve is derived in FRECOL from estimates of worst-case variations from the predicted power output at given time horizons. For instance, in power networks including a certain amount of wind power, such as the Nordic grid, the unpredicted power imbalance can for simplicity be assumed to be dominated by the fluctuations in produced wind power. Worst-case variations from the predicted wind power output within several horizons into the future, Δt, were estimated by [13] for a specific wind farm.

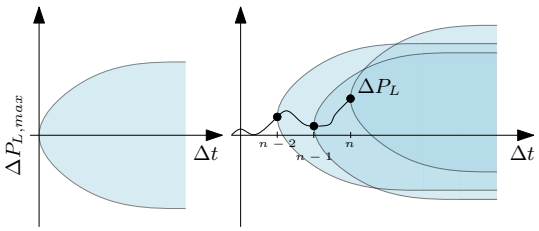


Fig. 9: Area defining the constrained random disturbance $\Delta P_{L,max}$ (left), and a time realization of $\Delta P_{L,max}$ (right).

The documentation in [4] provides further explanation on the generation of these constrained random disturbances.

V. Demonstration of the tool

This section presents the simulation results given by FRECOL in three distinct cases. The parameters used in the simulation are the default values suggested in [4]. The nominal frequency is 50 Hz and the FCR, FRR and RR power reserves are 330, 500 and 2500 MW, respectively.

Fig. 10 plots the results of a two-and-a-half-hour simulation of the controlled system. The continuous red line in plot (b) represents the pseudo-random disturbance sequence generated by FRECOL. It presents mostly mild imbalances, as expected in most cases. Under frequency control, and with the mild disturbance scenario, the frequency in the system is kept close to nominal and without incidents, as shown in plot (a).

The simulated responses of the three generation services to the frequency variations are represented by the patterned blue lines in plot (b), which clearly evidences the functions of each service. As expected from the proportional control law and the two-pole model, the response of the FCR service resembles a symmetric and filtered version of the frequency signal, this way providing for the quick stabilization of the frequency. The response of the FRR service, on the other hand, closely follows the power imbalance to restore the energy in the system and keep the frequency at its nominal value. As time progresses the FRR signal becomes more distanced from the load signal because the RR service slowly activates to replace it.

Fig. 11 plots the evolution of the controlled system for two and a half hours in response to a second pseudo-random disturbance sequence generated by FRECOL. The disturbance is shown in the continuous red line in plot (b) and is significantly more severe than the first, with two consecutive surges in demand of approximately 400 MW in 15 minutes.

The FRR control loop is fast enough to follow the demand but reaches its limit before the RR service fully activates. The consequent power imbalance leads to a sustained frequency deviation, as shown in plot (a) between 1 and 1.5 hours.

The slow activation of the RR service could suggest the need for a more aggressive control tuning. It should be noted, however, that in industrial practice the RR service is manually controlled by an operator. It is thus expected that the operator may vary the aggressiveness of control to the severity of the situation. Possible ways of mimicking this nonlinear reasoning with automatic control include the use of the squared control error as regulation signal or to have different control gains for different operating points of the system (gain scheduling).

Fig. 12 shows the results of a third simulation which exemplify a trying disturbance scenario to the system. In this case the pseudo-random disturbance sequence quickly changes from a significant excess of energy ($+600MW$) to a deficiency ($-600MW$), with a variation close to the worst-case scenario: 1200 MW drop in about one hour. The simulation by FRECOL shows that such a situation leads to saturation of the FRRs first in the positive and then in the negative sides of the reserve. Furthermore, this scenario actually forces the RR service to reverse direction. This is a slow change due to the large time constant of this service, so after 2.5 hours the RR service is actually increasing the energy imbalance. This leads to the saturation of FRRs and also the use of the FCRs for energy restoration. The frequency is shown in Fig. 12, which evidences a sustained deviation of the frequency after 2.5 hours and a frequency incident (over 50.1Hz) around 3 hours.

VI. Conclusion

This paper presented an open-source educational software tool for the long-term simulation of power system frequency control. The tool is aimed at power and control engineering students and is available online. The parameters of the system can be tuned by the user to resemble the desired network.

Section III explained how the models for generation and control take into account the specifics of each of the three control services, including modelling the manual control by the operator in the RR service. The tool also includes nonlinearities of the system. The paper considers a single control area. Extension to a multi-area power system would be achieved by replicating the model and including the power flow on the tie-line between control areas in the mismatch power signal and the regulation signal, as explained in [1].

An additional contribution of the tool, presented in Section IV, is the generation of random disturbance sequences. The results, in Section V, showed that these disturbances resemble realistic imbalance scenarios and the responses simulated by the tool agreed with the expected system behaviour.

It should be noted that the random disturbance generation feature facilitates extensive statistical analyses of power imbalances, control system performance and sizing of reserves.

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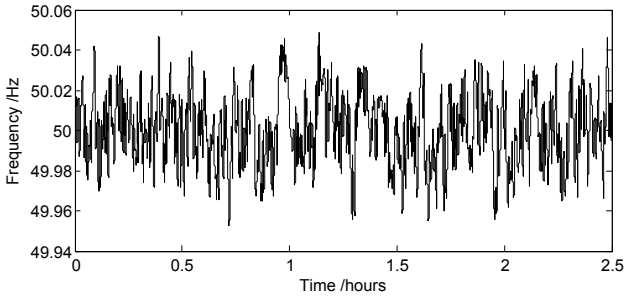
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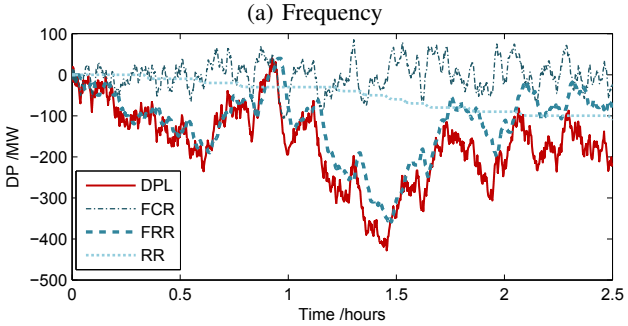
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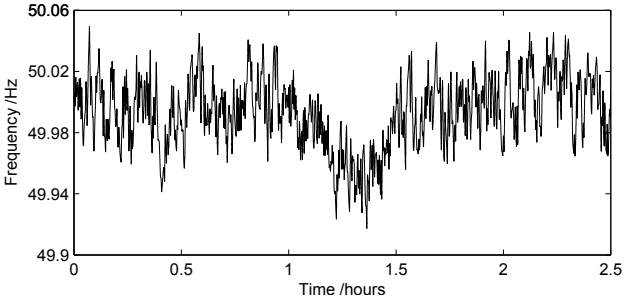


(a) Frequency

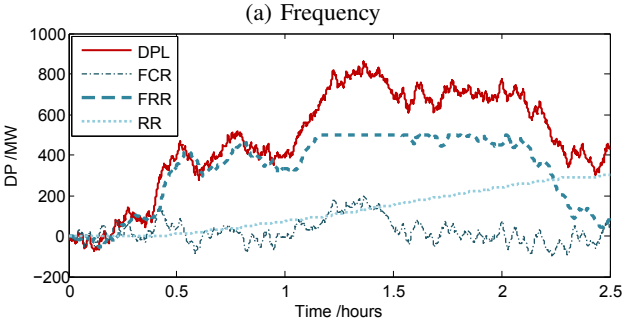


(b) Disturbance and generation services

Fig. 10: System response to power imbalance DPL

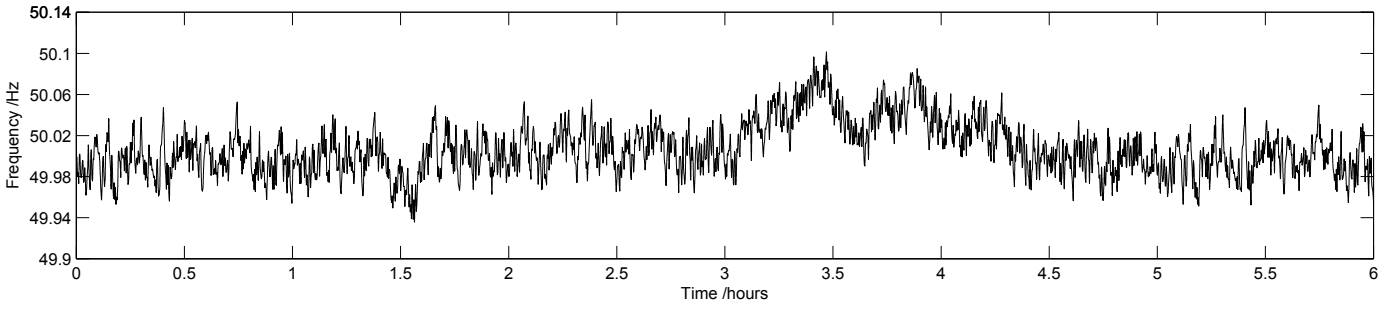


(a) Frequency

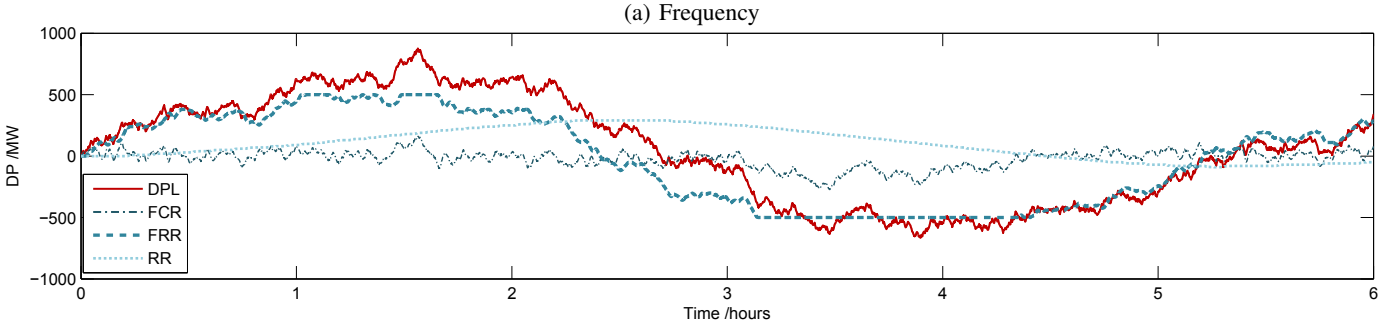


(b) Disturbance and generation services

Fig. 11: System response to power imbalance DPL



(a) Frequency



(b) Disturbance and generation services

Fig. 12: System response to power imbalance DPL

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