Reliable Power Generation for Ukraine

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Reliable and safe grid operation requires a balanced system at any time.

Introduction

As of today, the Ukrainian power system is in disruption. The power supply is currently based on nuclear power in the range of 40% in summertime to 60% in wintertime while thermal powerplants mainly based on coal have a constant share of about 35% over the year. High fuel utilizing CHP plants reached in the recent years a share of up to 13% while hydro power generates up to 8% of the daily power mix (see Fig. 1). Renewable power based on wind and PV is growing and will reach a significant market share pushed by governmental decisions in the upcoming years.

In addition to modernization, the decision was made to connect to the centralized European grid (ENTSO-E) and increase the share of renewable power which requires an adaption of and new investments into the energy system. Today mainly the coal fired thermal power plants and pumped-storage power plants cover the daily peak demand operating from the morning to the evening and be shut down over night. This stresses the equipment causing many expensive outages. With an increasing share of wind and PV in the grid not only the daily demand peaks will have to be balanced. Also, the intermittency of renewable generation must be backed up with short response times in the residual load operation, decreasing the average operating hours per start. Coal fired generation will not have the capability for such short response times required to maintain a stable frequency. The demand for re-dispatch, residual load operation and grid balancing services will increase to fulfill the European grid connection requirements and maintain a stable power supply.

Fig. 1: Power mix in Ukraine [1]
Impact of EU (ENTSO-E) regulations to power system operation

The major requirement for safe grid operation is that consumption and production of active and re-active power is balanced out within the limits defined by the grid codes and regulations of the authorities. Considering the trend to decarbonize and the change of power mix towards intermittent renewables (Wind and photovoltaics (PV)), the European Union together with ENTSO-E have released a new set of regulations defining the conditions for the European central grid between 2015 and 2018. All aspects like generation grid stability, grid restoration or emissions been evaluated and if necessary, adjusted to a grid considering the planned increased share of renewables. The technical requirements and boundary conditions within the regulations highly depend on the size of the generators.

As a main change in regulations the generators must be capable to operate in disturbed conditions with over- and underfrequency as well as over- and undervoltage as shown in Fig. 2.

The range of disturbed operation has been extended compared to the past regulations. This will be valid especially for new generators but with a grace period also for existing generators in case of significant modifications of the power equipment.

The Transmission System Operators (TSOs) are obliged to permanently monitor their regulation zones and initiate all measures necessary to stay within the defined limits. An exchange to neighboring zones is allowed (especially in emergency situations) but should not be the standard. Even when the generators must be capable to operate within the limits defined in Fig. 2, the target of the grid operators will be to keep the grid frequency within a range of ± 0.2 Hz for stationary condition with a maximum deviation of ± 0.8 Hz for short term dynamic grid response. The maximum allowed time for frequency restauration will be within 15 minutes [2]. The activation time for the frequency stability (deviation > ± 0.2 Hz) and restauration reserve (deviation < ± 0.2 Hz) is less than 30 seconds [3]. Especially to keep the frequency stable within a market environment of high renewables penetration, the TSOs have to define the mechanical, synchronized inertia limiting the Rate of Change of Frequency (RoCoF) which protects the grid connected equipment. As wind and PV do not contribute to the real inertia, the remaining connected equipment must provide as much as possible to keep the overall system cost limited while keeping the risk of a black-out at a minimum.

Besides securing sufficient availability of generation, back-up and emergency reserves, the TSOs must develop a market mechanism to optimize the utilization of the installed equipment. One way to ensure the lowest possible total system cost is to use several merit order lists for all necessary services along the power generation and balancing services of the power supply value chain. The availability of active and re-active power, short circuit power, phase angle, stability, and inertia must be optimized on dynamic, short, mid and long term time scales to ensure a stable and reliable grid operation. In addition, black-start and grid restoration capabilities etc. must be taken into account [4]. Some services must be available at any time like real, mechanical inertia for dynamic frequency stabilization, or short circuit power for safe grid operation while other services can be not synchronized and actively managed and connected as required. The evaluation criteria per grid service are defined in Fig. 3.

The possible solutions should be ranked in a merit order list to identify the priority of their utilization considering the activation mode, preparation time, time to full activation, the minimum and maximum regulation volume, and the time they can get activated, the de-activation time and a lock-out period for each grid service. To be able to operate the grid in the most cost efficient way, the EU required in
their standards [4] that those generators should come to dispatch first which provide the highest accumulated value across all merit order lists. This means that even in case of a solution is the best for one service required and others can provide the same solution with a lower ranking in merit order, those should be dispatched first according to their higher stabilizing contribution to the entire system. Even in case the costs are slightly higher for the grid operation, additional dispatch due to other necessary grid services like for reactive power compensation or short circuit power might be avoided.

**Impact of renewable power generation on safe grid operation**

In the classic, centralized grid structures, large conventional power plants generate the power which is transported at high voltage and distributed via medium and low voltage grids to consumers. Due to the inherent properties of such large, synchronized generation equipment, they do not only provide active power. They currently also contribute to balance the frequency due to their high inertia and they compensate the re-active power necessary for transmission and distribution grids. They also provide re-active power for the local grid and consumers demand important to keep the voltage balanced. In addition, they provide short circuit power to enable the detection of faults (and their locations) within the grid.

As Wind and PV only produce energy depending on weather conditions, the hereby caused volatility in the grid becomes an additional contributor to grid imbalances. To keep the frequency stable, additional flexible generation will be necessary on time scales < 15 minutes. For longer time scales, the remaining equipment will need to operate in residual (or part) load operation which reduces their overall power output. Part load efficiency and flexible operation becomes more and more important. Due to the connection of wind and PV via inverters, their contribution to re-active power compensation is very limited. In addition the locations are chosen due to high irradiation or wind profiles while the re-active power must be compensated close to the demand centers to keep the losses at a low level. The impact of an increasing share of renewables to the momentary power mix is described in Fig. 4.

Integrating renewables into an existing centralized grid environment up to a share of 30%, still grid balancing can be managed with the remaining equipment for e.g. lack of predictability of RE generation, shortage of re-active power compensation and reduced inertia in the grid. The only impact is that the (existing fossil) generation units will be forced to residual load operation which requires an increasing demand in operational flexibility capabilities. Beyond a RE share of 30%, the frequency and voltage becomes more and more volatile, and locally the re-active power must be compensated as the capability of wind and PV is limited. Increasing the share of renewable power further beyond 30% will cause higher instabilities in voltage and require very high levels of compensation capabilities on all time scales (i.e. in Germany more than 150 re-active power compensation devices will be required according to the latest grid development plan). The increasing share of renewables will also result in a shut down of generation capacity as financially the operation gets too expensive. For longer terms, storage capacities must be developed to ensure sufficient reserves in case renewable generation is not available. The grid will have to be operated in residual load mode which increases the operation costs significantly.

![Fig. 4: Impact of the momentary share of intermittent renewables of the grid operation.](image-url)
not available. Large, synchronous rotating power equipment can provide the higher short circuit power necessary during a grid failure. This current allows the grid operator to locate the failure and switch off the failed segment of the grid without the risk of a blackout. As renewable power producers cannot provide sufficient short circuit power (risk of inverter damages), the grid operator can not identify the damaged segment within the grid by the high fault current and has to shut down a large area of the grid to limit the damages. The separated grid segments must have the capability of operation in island mode. This can be achieved by transitioning to de-centralized power generation operating equipment with high specific inertia, re-active power capabilities, etc. The area containing the fault must be investigated to localize and separate the fault for repair. The segments must be capable for black-start to be able to get connected to the grid.

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Based on the high share of intermittent renewables the required operating pattern will change. A new segmentation for the power and balancing equipment is proposed as shown in Fig. 5. Beside of the standard market segments of base, intermediate and peaking load operation, the residual load remaining from the renewables requires a higher flexibility. Technical parameter like operating hours per start, share on part load operation and part load efficiencies become more important to the evaluation of solutions. As the tertiary response has similar operating pattern and covers the same time range as the flexible peaker so both have been merged.

The power demand in Ukraine during daytime is currently up to 25 GW. Considering a planned installation of Wind and PV of about 13.1 GW$_{\text{peak}}$ and an assumed utilization of 90%, the momentarily share is expected to be in the rage of up to 50%. During these times, after an incident in the grid, an impact on frequency and voltage stability in the dynamic (< 1 s), fast (1 s up to 5 min) and short time scale (5 min to 15 min) is expected.

In Fig. 6 the system from ENTSO-E is visualized, describing the process of (1) keeping the frequency stable after a disturbance in the grid, (2) restoring the frequency and replacing the activated frequency restoration units by reserve and (3) bringing the system back to normal operation [5]. These steps are discussed in the following chapters.

**Frequency Restoration Process (FRP)**

After the immediate response has stopped or, at least, limited the change in frequency within sub-second to a few seconds, the frequency must be restored to normal level by the frequency restoration process within the first up to fifteen minutes after the incident. These services are within the Primary and Secondary Reserve markets which consider a variety of different ancillary services. The frequency restoration can be activated by automatic and manual systems. It can be reached based on two basic principles.
A certain share of equipment should operate synchronized to the grid with a mandatory Fast Frequency Reserve capable of short activation times and high load change rates. These Ancillary Services (Mandatory Frequency Response, Firm Frequency Response, Balancing Mechanism Hot stand-by but also Obligatory Re-active Power Reserve) should be automatically activated to ensure fastest response times. To ensure the highest efficiency for the power generation of the hot reserve, hybrid systems consisting of combined cycle generation and batteries would technically be the best solution. The generation part should be operated with highest possible efficiency providing in addition to the required active power also re-active power and real inertia to the system for FCR. The Battery Energy Storage System (BESS) balances out short-term fluctuations and due to the fast response time also provide synthetic inertia for FCR. Due to the capability of the BESS, it also can be used as a system for Demand Side Response.

An operation of the conventional generation unit at part load without hybridization is also possible, but with slower response times for increase or decrease of the power output (depending on the individual flexibility characteristics). In this case the generation units also contribute with high mechanical inertia and reactive power capabilities to the FCR. After synchronous reserve is activated and increase power output, fast starting non-synchronous equipment is activated automatically or manually. According to individual start-up times, additional generation must synchronize to the grid. Due to lack in power and the lower frequency, the additional generation must exceed the loss in power to recuperate the grid frequency. This additional power can be provided by RICE and aero-derivative GTs with start-up times at 5 minutes (or below) or with industrial or utility size GTs in simple cycle with start-up times in the range of 10 minutes. Economic viability mandates the consideration of specific cost for maintaining fast start conditions, e.g., keeping the equipment, cooling water or oil at operational temperatures if necessary. The costs per start for equipment out of operation for longer time periods until the Reserve Replacement Process (RRP) is initiated can significantly impact plant economics.

The required minimum secondary reserve was defined by ENTSO-E [11] according to Fig. 7.

For Ukraine with a demand of up to 23 GW, the minimum secondary reserve about 310 MW would be required.

**Reserve Replacement Process (RRP)**

After the missing power has been added to bring the frequency back in the range of undisturbed steady state operation, the aim of the further restoration is to increase the systems efficiency. The time until non-synchronized, high-efficient power utility size power generation is started up and connected to the grid or steam plants with slow acting boilers can increase their power output must be bridged. With start-up times of less than 15 minutes industrial size gas turbines can be started up and closing the cycle whenever allowed by the steam conditions. With this concept the electrical generation efficiencies during the secondary/tertiary response periods can reach 58% and more.

The entire range from immediate response over primary and secondary to tertiary response can also be covered by hybrid solutions combining storage technologies with highly efficient fossil power generation equipment.

**Residual load**

As renewable energy is not always available, this power source must always be backed up by reliable power to satisfy power demand. Depending on the accuracy of the weather forecast, the residual load can be traded in the day-ahead or intra-day market. Highly efficient power equipment as described in the RRP section can also be used for standard base load operation in this segment. The lowest generation costs and available fuels can be utilized.

Power plants for residual load operation can be designed to also stabilize frequency and voltage even when the active power is not required in that moment (provided by e.g., renewables). Technically, this can be realized by adding a clutch between the driving GT and the generator to allow the generator to operate as Synchronous Condenser (SynCon). A SynCon can stabilize voltage and add synchronous, mechanical inertia to the grid for dynamic frequency stabilization, even in times when enough active power is available.

Further low-cost equipment can also be added for hybridization, e.g., a fly wheel, increasing even more the usability of existing equipment in multiple applications across the power generation and grid stability value chain (see Fig. 8). This approach guarantees the highest equipment utilization while keeping the overall system cost at a minimum.

**Voltage stabilization**

The control and stability of the grid voltage becomes an additional challenge in a wind and PV penetrated grid environment. The possibility to “transport” re-active power is limited by losses in the power system. As with an increasing share of renewables the distance between generation and consumption will increase, the demand for inline compensation...
will increase accordingly but also local compensation capabilities on the demand side will increase. In case the demand will not be compensated, the grid will see major voltage deviations.

The most cost-efficient way for compensation of reactive power is to combine it with the generation, which can be done with synchronous rotating equipment in use for generation anyways. Nevertheless, Wind and PV just have limited capabilities of provision of reactive power and their location might be far away from the demand centers. This results in an increased demand of compensators close to the demand centers operated by the TSOs.

Two different basic technologies are available for the compensation, 1. Static VAr (Volt Ampere reactive) compensation and 2. the use of Synchronous condensers (SynCons). The best available technology for the reactive power compensation is the static VAr compensation which is based on semiconductors approximating the required sinus wave on several levels. To add benefits to the static VAr compensation, a combination with supercapacitors, electrolyte capacitors or fast batteries might add additional synthetic inertia for frequency stabilization.

The second available technology is the use of SynCons which are synchronous turbogenerators connected to the grid. They operate just by the reactive power compensation with quite low operational losses (decoupled from a turbine as drive). SynCons can be installed as greenfield solution but also converted from existing old power plants taken out of service due to low efficiency of the turbine or getting replaced by other power sources (more efficient fossil or renewables). As SynCons operate connected to the grid, they also provide dynamic inertia and short circuit power. Latter turns very important in a short circuit event and keeps the system operating which helps identifying the location of failures in the grid, thus limiting the impact of faults in the whole power system.

**Application of the frequency stabilizing to the Ukrainian market**

As discussed, the grid must be balanced out all time scales according to Fig. 5. The dynamic requirements to stabilize the frequency can currently be covered by nuclear and coal fired generation sufficiently. Additional requirements due to connection to the ENSTO-E-zone might be covered by battery storage systems to have the multiple use and synthetic inertia but also for load shifting operation using renewable access power or utilizing the minimum load power from the must operate coal fired plants.

As the coal fired generation which is currently also used for grid stability purposes in the minute time scale plus provides high emissions and the equipment is well aged new balancing equipment is planned. According to the requirements from ENTSO-E (see Fig. 7), the demand for secondary response is in the range of 300 MW in very flexible generation. Nevertheless, in Fig. 9 the power mix of typical days in summer and winter are shown. Based on the power mix and the must operate requirements of the thermal generation a balancing demand in the range of 2 GW is required which requires additional 1.7 GW of reliable and highly efficient generation with limited flexibility requirements.

![Fig. 8: Example of very flexible power plant design delivering the highest technical and economic value for generation and grid stabilization in a highly renewable penetrated grid environment. The approach can be used for large utility power plants or also for industrial or aero derive driven power plants in multi-unit configuration.](image)

![Fig. 9: Power mix and demand in Ukraine Mar. 4, 2020, and Aug. 22, 2019. In the bottom of the figures the required peaking demand is displayed [12]. Each dark green box under the demand curve represents a proposed (2x1) CCGT plant, light green indicates highly flexible simple cycle aero derivative gas turbines fulfilling the complete flexibility requirements for secondary and tertiary ancillary services.](image)
Conclusions

EU standards mandate that the highest the accumulated value of a single power contributor for the power system is, the higher the dispatch ranking of this contributor should become according to (EU) 2017/2195. The technology should be evaluated and chosen considering the entire impact to the power system to avoid building specialized equipment which can only provide a very limited part of the ancillary services. A qualitative comparison of different generation technologies has been given in Fig. 10. On the x-axis the evaluation of the parameters for the ranking within one merit order list shown in chapter Fig. 3 are displayed while on the y-axis the accumulated value across all merit order lists are displayed. As not all regions within the centralized European grid have finally been checked and confirmed by ENTSO-E [8], the power generation and all paid services in UK [13] and Ireland [14] have been evaluated as reference. The size in Fig. 10 indicates the emission of greenhouse gases considering equivalent CO₂-emissions (CO₂ emissions plus methane slip).

Fig. 10: Qualitative comparison of generation technologies considering the ranking within the merit order positions according to (EU) 2017/2195 [4] for the several grid services versus the overall benefit considering all grid services as described in (EU). Grid services mean support of generation, grid balancing for frequency, voltage, and short circuit power as well as grid restoration capabilities.

Within the baseload column the steam fired plants (hard coal) provide a high level of mechanical inertia with their large power trains and can balance the re-active power demand due to the large size of generators. Yet, the emission of greenhouse gases is quiet high for coal plants. A significant decarbonization can be achieved using clean natural gas as fuel for base load operation. Beside burning gas in steam boilers and using the steam turbine technology to produce power, two different basic technologies are available, 1. Reciprocating internal combustion engines (RICE) and 2. Gas Turbines (GTs).

RICE provide a good simple cycle but a poor combined cycle efficiency. Due to their small unit size of up to 20 MW electrical output and their high maintenance requirements for standard medium speed engines, the operation of a power plant significant for the grid becomes quite complex in a multi-unit approach with many gensets. The part load efficiency of the entire power plant is good (if units do shut down and the remaining ones run basically at full load close to the efficiency optimum). The contribution to grid stability is limited as the engine itself does not provide significant mechanical inertia, see Fig. 10 and, due to the small turbo-generators connected, a re-active fast power regulation is not possible. The low inertia and poor re-active capabilities require additional grid balancing equipment for stability (significant increase in capex).

Depending on the size of the plant and the grid environment, GTs in single (utility) or multi-unit (industrial) configuration provide highest electrical efficiency in combined cycle and, using the waste heat from the GT, generating steam in a Heat Recovery Steam Generator (HRSG) and leading to additional electric power produced with a steam turbine. The speed of the turbine is much higher compared to RICE and the rotors (blades and shaft) provide a significant higher moment of inertia higher than RICE. The synchronous connected inertia for dynamic frequency stabilization provided by GTs is orders of magnitude higher than RICE. Especially the multi-unit combined cycle power plants also provide an outstanding part load efficiency important for residual load operation within a renewable dominated grid environment.

This configuration delivers the highest value and applicability across the base load and grid stabilizing requirements of the grid.

The RICE in use for grid stability just provide a good operational flexibility for the FRP while the dynamic response is very limited. Their ease to start and short start-up time help in the case after blackouts and enable non-synchronous FRP, but in winter times they must be kept warm which relate to high costs for the operator to be able of utilizing this advantage. The dispatch of RICE-based FRP should only be very limited within a grid environment given the poor economics. Similar start-up capabilities can be achieved using aero derivative GTs with outstanding ramping rates for frequency restoration. As in case of a massive loss in power with blackout potential, a large power output per unit is favorable or even required to enable an easier dispatch process and a better operability of the power generator. In addition to the fast power output, the higher re-active power of the larger synchronous generator can stabilize the voltage, provide a higher short circuit power, and the frequency is better secured by the higher inertia in the disturbed grid under
restoration condition. A similar benefit can be gained using industrial GTs in open cycle. They provide a higher mechanical inertia but will have a slower start-up time. Due to the multi-unit approach, both solutions can be spread to critical locations. In case a large grid needs to be secured, a large, utility scale simple cycle GT plant in multi-unit configuration can also be used.

This concept has recently been contracted in Belarus where four GT-based power plants in the range of 100MW to 300MW based on several 50MW generators will run as peaker. These gas turbines provide an ideal offer of economic peaking power, back-up and provide per unit synchronized the highest inertia, re-active power capability and short circuit power. Focus had been taken in choosing the locations carefully for the optimum grid support taking the optimal advantages for stabilizing facilities.

References

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