Reliable Power Generation Supply for the Republic of South Africa

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Summary

Hydrogen is currently in evaluation to play a central role in the decarbonization of the energy and transport sector. Produced by electrolysis of water using power generated by wind or PV is one of the easiest solutions for a long-term storage of green power. Due to its physical properties, the use of hydrogen or blends with other gaseous fuels in a Reciprocating engine has an impact on fuel system, design and performance as well as the emissions.

Using hydrogen in reciprocating internal combustion engines (RICE) might result in a reduction of CO_2 as the H-C-ratio in the fuel increase. Due to the high flame speeds higher speed RICE would be in favor using hydrogen or blends containing a high share of hydrogen by additional increase of engine speed. Using higher compression ratios would result in an additional increase the efficiency. Considering new materials in the design and a selective catalyst reactor (SCR) hydrogen would be a good option for emission reduction within high speed RICE.

Currently utility scale power generation is based on medium or low speed RICE. For these units the use of hydrogen and its blends has a high impact on the power output, maintenance schedule and operation. H_2 contents of higher than 38% require a downrate of the Engine due to the low calorific value per volume. The risk of early / auto-ignition or knocking requires a better control of the fuel air mixture and the compression stroke. Highly efficient, compression ignited engines intended to run on a high share of hydrogen will require a pilot flame mainly based on fossil or e-fuels which will result in a remaining CO_2 emission. Due to the main application in a renewable environment for grid stability, the engines will be operated in cyclic mode which increase the risk of water migrating into the lube oil. Hydrogen induced embrittlement of high yield strength steels and copper alloys used in valves, valve seats or piston rings limit the potential of retrofits to operation with hydrogen blends. The use in engines designed for use of natural gas require major changes of the entire systems and beyond 38% of hydrogen content the unit must be de-rated due to the low energy heating value per volume.

Reliable Power Generation Supply for the Republic of South Africa

Introduction

South Africa ranks amongst the top ten coal producers in the world. Almost 70% of this coal production is used to generate electricity within the country. This electricity production method has a direct influence on the degradation of the environment. An extensive and aging distribution infrastructure for centrally generated power is used to reach communities in remote areas of the country and increase distribution losses. The South African Department of Mineral Resources and Energy (DMRE), in collaboration with the National Energy Regulator of South Africa, developed a procurement program for the development, procurement, and implementation of alternative power projects to supplement its fossil fuel-based production. South Africa has a total electrification rate of 85 %, but despite this fact, almost half of the rural population in the country is still without electricity. This lack of access to electricity impacts the economic growth of the country and contributes to the climbing poverty rate and diminishing quality of life in the rural areas.

Due to rapid population growth, an increase in economic activities and an aging coal fleet South Africa is unable to meet the demand from the national grid. This imbalance results in the current load shedding crisis. It is evident that South Africa can no longer rely on one primary source of energy. The priority is now to develop a diversified energy ecosystem as a primary requirement to enable the country's sustainable development. The South African Government adopted short term policies and frameworks to assist them in resolving the load shedding crisis. One of these frameworks includes upgrading the existing electricity infrastructure and integrating smaller, locally managed power stations into the national grid.

In 2019, the Department of Mineral Resources and Energy issued an Integrated Resource Plan (IRP2019). In 2020 a RFP for emergency power in the form of the Risk Mitigation IPP Procurement Process (RMIPPPP) to source 2000 MW, the RFP is technology agnostic. First indications are that hybrid solutions will provide the lowest energy tariff's for the dispatchable power.

The outlook to 2030 forecasts an even much higher investment into renewable power with a high share of sources like wind or photovoltaics (PV) which might achieve a significance of than 30 % of the momentarily produced power and much more during daytimes. This will have an impact of the grid operation and create challenges on short term grid stability but also push the reliable power generation technologies towards a residual load type of operation requiring higher operational flexibility. In addition it turned out in several countries integrating intermittent renewables already that in the order of magnitude of 30 % and higher the safe and reliable operation of the grid becomes more challenging. Shortages of inertia and fast frequency response capacity will require additional efforts for frequency stabilization, an increase of re-active power compensation must be considered for voltage stabilization (see Fig. 1 for the example of Tennet-Zone in Germany) and short circuit power for failure detection of the grid operator are just some topics which need to be considered.

Fig. 1: Increase of re-dispatches from TSO for frequency and voltage stabilization caused by an increase of renewables and reduction of stabilizing, syn-chronous generation technologies in Tennet-Zone, Germany

This paper will investigate how to develop a diversified energy ecosystem, capable of meeting South Africa's energy needs.

Impact of renewable power generation on safe grid operation

In the classic centralized grid structures, like currently in the Republic of South Africa (RSA), 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, sychronized generation equipment, they do not only provide active power but also contribute towards balancing the frequency due to their high inertia for dynamic frequency stabilization and they compensate the re-active power necessary for consumers and the operation of transmission and distribution grids. In addition, they also provide short circuit power for a safe operation of the grid enabling the detection of the location of faults within the grid.

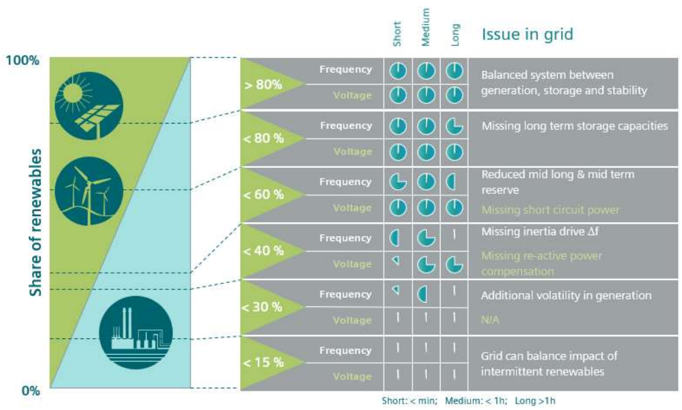

Fig. 2: Impact of the momentary share of intermittent renewables of the grid operation.

As intermittent renewables like wind and PV only produce energy depending on weather conditions, the hereby caused dynamic 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 flexiblility requiring 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. 2.

Integrating renewables into an existing centralized grid environment up to a share of 30%, grid balancing can still be managed with the remaining equipment for e.g. lack of predicatability of renewables 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 renewables share of 30%, the effort of balancing the current power mix as well as the frequency and voltage will be increasing more and more, 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 renewables integration and grid development plan). The increasing share of renewables will also result in closure of reliable thermal generation capacity as operations gets too expensive pushing those out of the merit order dispatch rankings. For the longer term, storage capacities must be developed to ensure sufficient reserves in case lacking renewable generation.

Larger, 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 global blackout. As renewable power producers cannot provide sufficient short circuit power (risk of inverter damages), the grid operator cannot 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 start on their own and get connected to the grid.

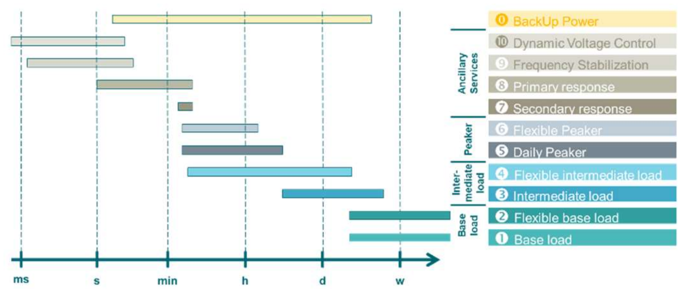

Fig. 3: Operating pattern based power market segmentation [Siemens].

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. 3. Beside of the standard market segments of base, intermediate and peaking load operation, the residual load, so the generation to fill the gap from the fluctuating renewable generation to the demand, requires a higher flexibility. Technical parameters like operating hours per start, part load turn down 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, both have been merged.

Application to the South African power market

The development plans of the power mix for RSA have been investigated in several studies considering multiple scenarios developed by J. Wright et. al. [2], [3] and the Department of Energy [4]. These studies give an outlook on the de-carbonized future of RSAs power environment.

Nevertheless, different solutions provide different physical properties for generation as well as grid stability purposes. The European Union introduced in their specification EU-(2017)

2195 [5] a method how to keep the power system stable with the lowest systems cost. All generation units must be evaluated based on merit order lists according their contribution to the entire grid including generation and all services necessary for grid stability purposes. Those generation sites contributing with highest overall value to the system should get dispatched first. Investment and dispatch decisions based on this criterium can reduce systems cost across generation and reliable grid operation. Minimizing the investment cost (CAPEX) across the power supply chain is also a requirement in the South African Grid Code [6, chapter 7.2.3] which can be achieved by evaluating different technologies. Inertia for dynamic frequency stabilization, re-active power compensation capabilities for voltage stabilization and short circuit power (SCP) for a failsafe operation of the grid must be considered in the financial evaluation as well as on the generation side the efficiency, CAPEX, operational parameters and other values. Especially for new, decentralized equipment in areas with high fuel prices the option to close the cycle (means adding heat recovery based power generation like steam turbines or ORC) to boost the efficiency might be of benefit.

Daily peaker in residual load operation

As renewable energy is not always available, this power source must be backed up at any time by reliable power generation options 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 markets. 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. To ensure future proof operation the thermal generation equipment should be capable to operate on a wide variety of mainly gaseous fuels.

Besides the base load operation, which can easily be covered by existing coal and nuclear plants (and potentially by gas plants in future), the high share of renewable generated power raise specific requirements to cover the daily peak demand. In case the weather forecast does not allow for wind and PV, reliable daily peakers must provide the power covering the peak hours in the morning and evening to the reduction of demand during the night. When PV is forecasted, only the time in the morning between the increased demand and sun raising needs to be covered and vice versa in the evening. In case renewables are present and cannot ensure the full power supply, the reliable peaker plants must be capable to operate flexible in oder to provide the necessary reliable residual load. Sufficient capacity with ramp rates defined by the renewable generation must be available to keep the frequency within the limits defined by the South African Grid Code [6].

Inertia for dynamic frequency stabilization

In the unlikely event of a large disturbance within the South African grid, the frequency will immediately decrease in case of an undersupply or increase in case of an oversupply. The resulting target frequency must stay in the range between 49 Hz and 51 Hz for continuous operation and between 47 Hz and 49 Hz as well as 51 Hz and 52 Hz for a limited time. The frequency response in case of a disturbance is defined by the amount of MW of the over-/undersupply. The time required until the limits in frequency are reached will be defined by the Rate of Change of Frequency (RoCoF) defined in Hz/s. The RoCoF is limited by real or after a few 100 milliseconds by synthetic inertia until the generation units for the Fast Frequency Response (FFR) can react with increasing or decreasing their power output. Changing the power mix from reliable synchronous generation towards an increasing share of inverter connected generation units like wind or PV will reduce the grid stabilizing inertia resulting in an increasing RoCoF which might damage synchronous equipment. A limit of RoCoF is currently not defined in the South Africa Grid Code [6] for thermal units but defined in the connection requirements for wind turbines with max. 1,5 Hz/s. As in the country large rotating equipment is in operation, the RoCoF should be limited to a value of 1 Hz/s.

G.A. Chown et. al. [7] have investigated the impact on RoCoF with an increasing share of non-synchronous renewable like wind and PV in the South African grid. According to different scenarios of grid development plans, up to 24 GW of non-synchronous generation should be installed by 2030. This would result in a share of up to 41% in the *Least Cost scenario* which would replace the large rotating equipment of coal fired power plants. The specific inertia constants of the most important generation technologies in South Africa are listed in Table 1. It must be considered in the evaluation that the generation units must be synchronous in operation to provide the inertia.

Technology	Inertia constant [MWs/MVA]
Coal	2.0 – 4.0
Nuclear	5.0
RICE	2.0 – 2.4
OCGT	6.0
CCGT	9.0
Hydro/Pumped Storage	3.0
Wind	0.0
PV	0.0

Tab. 1: Selected specific inertia constants for various technologies [7], [8]

After detection of the frequency imbalance, inverter connected storage and synthetic inertia like batteries must be activated. During this activation time, only synchronous rotating equipment can provide the necessary inertia to limit the RoCoF and to prevent the frequency to change beyond the critical black-out frequencies. Several investigations have been carried out resulting in a necessary share of real and synthetic inertia of about 1/3 of synchronous and 2/3 of inverter connected, synthetic inertia required for a safe operation of the grid [9], [10], [11].

Voltage stabilization – re-active power

Replacing reliable synchronous generation technologies with intermittent, non-synchronous but inverter-connected generation technologies like wind or PV, not only fluctuations of the frequency have to be considered. According to the grid code requirements in South Africa, the voltage level should stay within the normal voltage operation range between 90 % and 110 % p.u. For the connection of wind generation units to the South African grid, the site must be capable to provide voltage within the range of power factors of 0.975 for generation sites ≤ 20 MW and 0.95 for sites > 20 MW [12]. Both values are symmetric for leading and lagging voltage compensation.

In case synchronous thermal generation equipment (with their high ability to compensate re-active power) will be decommissioned, this will result in much higher deviations on the voltage and increased dynamic fluctuations of the voltage in the grid. The higher fluctuations of the voltage increase the risk of unplanned shutdowns of industrial production caused by emergency shutdowns of electrical drives to protect the systems.

The most cost-efficient way for compensation of re-active power is to combine it with the planned, decentralized generation, which can be done with synchronous rotating equipment in use for local generation anyways. The in-line compensation is key here: due to increasing distances between renewable generation sites (optimal wind and irradiation conditions) and the demand centers, the higher connection losses will have to be compensated. Nevertheless, as stated in the grid connection requirements, wind and PV just have limited capabilities of providing re-active power and their location might be far away from the demand centers where the compensation has to occur. This results in an increased demand of compensators close to the demand centers operated by the TSOs.

Two different technologies are available for the re-active power compensation, 1. Static VAr (Volt Ampere reactive) compensation and 2. SynCons (synchronous condensers).

Static VAr compensation, based on semiconductors approximating the required sinus wave on several levels, is the best compensation method. Further benefits to the static VAr compensation can be added like combinations with supercapacitors, electrolyte capacitors or fast batteries which can add synthetic inertia for frequency stabilization of the grid. SynCons are basically synchronous turbogenerators connected to the grid. They can compensate re-active power with quite low operational losses (optionally 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 e.g. too low efficiency of the turbine or replacement by other power sources (more efficient fossil or renewables). As SynCons operate "synchronized" to the grid, they also provide inertia for dynamic frequency stabilization and short circuit power for safe grid operation. 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.

Handling of Low Voltage Ride Through events

Replacing large, synchronous thermal generators by non-synchronous, inverter-connected generation technologies like wind or PV, the ability to provide Short Circuit Power (SCP) will shrink significantly. In the South African grid code requirements for wind turbines [12] the low voltage ride through capability to be provided by the renewable sources is quite limited to 150 ms for a full short circuit on the outer power lines. This very short duration is not sufficient to detect a fault and switch off the affected power line(s). To be able to provide sufficient time to identify and clarify the disturbance (and its location) in typical grids, up to 30 seconds are required. This can only be provided by a synchronous rotating generator. The technologies utilized for synchronous residual load operation should also have the capability to provide as much SCP as possible to allow the safe operation of the grid.

Evaluation of the highest value for the grid

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. This method has been defined as a new standard by the European Union in 2017 when introducing the standard EU 2017/2195 [5].

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 maganed and connected as required. The evaluation criteria per grid service are defined in Fig. 4. The possible solutions should be ranked in a merrit 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. This means that in case several technologies competing to dispatch, not necessarily the one being the best for one particular service gets contracted, but that one providing the best overall grid contribution (all services, e.g. adding system inertia and therewith stability). Even with slightly higher cost for grid operation, additional dispatch contracts for other necessary grid services like reactive power compesation or short curcuit power can be avoided.

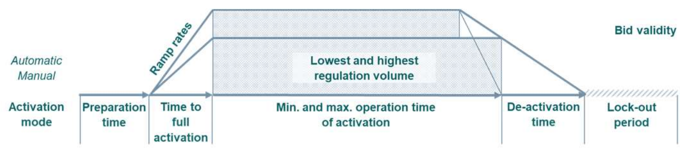

Fig. 4: Overview about the evaluation criteria for Merit Order lists per grid service according to (EU) 2017/2195.

Emissions and Financing

Environment and health protection are of growing concern in modern societies around the world. To incentivize environmentally sustainable decisions in power generation, project financing is more and more coupled to stricter emission targets. E.g. the EIB (European Investment Bank) announced in 2019 that fossil fuels based projects would only be given financing if specific CO_2 emissions do not exceed 250 g/kWh. This means the total fuel efficiency must be higher than about 80 % and exhaust heat needs to be used to achieve such levels. Furthermore, World Bank also sets limits to NO_x, SO_x, PM and some national legislation even require more stringent emission figures. Low emission power generation technologies will enable international investments and funding as more and more institutions only invest and finance sustainable projects.

Conclusions

The government of the Republic of South Africa has decided to invest into future generation technologies based on renewable sources like wind and photovoltaics and on natural gas. The targeted share of renewable power will have an impact on safe and reliable operation of the grid as well. To be able to receive outside funding for the projects a special focus should also be set on the new installed fossil generation technologies necessary for residual load operation and balancing services. To keep the overall systems costs as low as possible while developing the power mix and ensuring the security of the power supply it is important to consider the overall benefit of the technologies for the generation but also for ancillary services and safe grid operation. Other regions, e.g. the European Union, decided on a new dispatch ranking methodology that accounts for all benefits which a specific power producer can offer to the grid.

EU standards mandate that the higher the accumulated value of a single power contributor for the power system is, the higher the dispatch ranking of this contributor would be according to (EU) 2017/2195. The power technology should be evaluated and chosen considering the whole impact to the power system to avoid the need for 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. 5. On the x-axis the evaluation of the parameters for the ranking within one merit order list 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 (ENTSO-E) have finally been checked and confirmed, the power generation and all paid services in UK [13] and Ireland [14] have been evaluated as reference. The size in Fig. 5 indicates the emission of greenhouse gases considering equivalent CO_2-emissions (CO_2 emissions plus methane slip).

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. Nevertheless, the emission of greenhouse gases is quiet high for coal plants. Significant decarbonization can already 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).

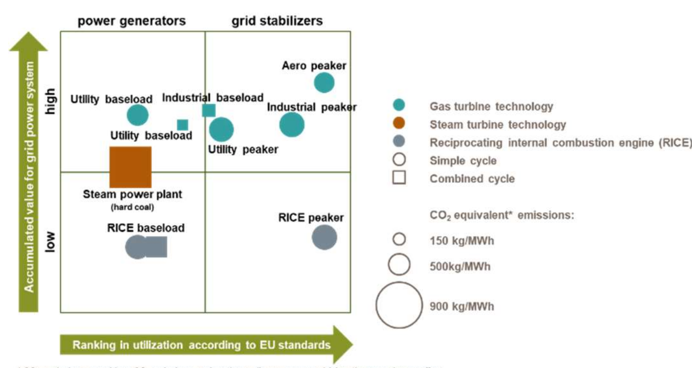

*Fig. 5: Qualitative comparison of generation technologies considering the ranking within the merit order positions according to (EU) 2017/2195 [4] for the several grid services versus the overall benefit considering **all grid services** as described in (EU). Grid services mean support of generation, grid balancing for frequency, voltage, and short circuit power as well as grid restoration capabilities.*

RICE provide a good simple cycle, but a poor combined cycle efficiency compared to GTs. Due to their small unit size of less than 20 MW electrical output and their high maintenance requirements for medium speed engines, the operation of a power plant with a power output significant for the grid becomes quite complex (too many units to handle). The part load efficiency of the entire power plant is good as gensets only operate when the power is required to achieve the optimum efficiency. But this operational behavior limits the contribution to grid stability as an engine itself does not provide significant mechanical inertia due to the small turbo-generators connected. A significant contribution to re-active power compensation and SCP is limited to those units synchronized to the grid. The low inertia, re-active power and short circuit power contribution will require additional grid balancing equipment for safe and reliable grid operation. Additional investment will be necessary at different sites requiring a variety of different technologies like batteries for synthetic inertia or synchronous condenser for re-active power compensation and short circuit power for Low Voltage Ride Through events.

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 mode. Using the waste heat from the GT, steam is generated in a Heat Recovery Steam Generator (HRSG) and leading to additional electric power produced in a steam turbine (ST). The rotational speed of synchronous turbines is much higher than that of RICE equipment and the GT and ST rotors (blades and shaft) provide a significant higher moment of inertia. 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 across all operational loads while adding grid stabilization for free.

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 black-outs 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 is typically 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. During massive power loss with blackout potential, a large power output per unit is favorable or even required to enable easier dispatch process and 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. To secure large grids, large utility scale multi-unit simple cycle GT plants can be the best solution.

This concept has recently been contracted in Belarus where four multi-unit simple cycle GT power plants in the range of 100 MW to 300 MW will run in peaking mode. These GTs provide an ideal balance between economic peaking power, back-up and the highest inertia per unit synchronized as well as re-active and short circuit power. Focus had been taken in choosing the locations carefully to optimize the grid support effects of the peaker plants.

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