The Future of the Grid: operating reliable power systems to achieve a clean energy transition

Discussion document on the public on-line training webinar on an Introduction to power systems held on the 7th of September 2023, 14:00 – 16:00

1. Introduction

Globally, the transition from traditional generators to high levels of variable renewable and distributed energy resources is already challenging traditional models of system operations. Yet achieving global net zero greenhouse gas emissions and universal energy access goals will crucially depend on reliable, stable, and decarbonised electricity systems. The reorganisation of electricity systems to integrate high levels of variable renewable energy (VRE) and the associated investment in grid infrastructure are critical interventions in meeting climate and development goals and South Africa's just transition aspirations but are not without their challenges.

A two-day international dialogue, learning and knowledge exchange on the effective operation of high variable renewable energy power systems was facilitated by the University of Cape Town, in partnership with the Presidential Climate Commission (PCC); and supported by the Australian High Commission in South Africa. It was held on the 13th-14th September 2023, Johannesburg, South Africa. An online public training webinar was held prior to the event on the 7th of September to introduce power system basics for a non-technical audience. This report summarises the outcomes of this public training webinar. A report summarising the key outcomes of the two-day international dialogue will be published in due course.

This training webinar builds on two previous dialogues hosted by the PCC related to energy system planning and operations.

- The first dialogue was held on the 14th of July 2022 and explored energy systems planning and balancing with a focus on how to balance electricity demand and supply in a manner that supports climate-compatible economic development.[1]
- The second dialogue titled Energy Dialogue: Energy Security and Technological Change explored electricity system reliability and sustainability in the context of technological changes. It was held on the 4th of August 2022. The content related to these dialogues are available on the PCC website.[2]

The online public training webinar focussed on two key topics. The first was an introduction to power systems concepts and theory from a technical perspective. The second topic was an introduction to power systems planning in the real world.

This report follows the structure of the webinar by first discussing the power system concepts and theory and secondly, discussing power systems planning in the real world.

2. Introduction to power systems: concepts and theory

This section provides a high-level summary of the key concepts and theories that need to be understood to gain a simple understanding of how power systems work and are operated. The key concepts discussed below include the power system as a complex system, power systems with and without variable renewable energy and power system frequency, stability, quality and reliability.

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[1] See: Energy Systems, Planning, and Balancing

[2] See: Energy Security and Technology

2.1 The power system as a complex system

The power system is a complex system. A generalised perspective of complex systems such as the power system identifies several features, which are depicted in Figure 1 below.

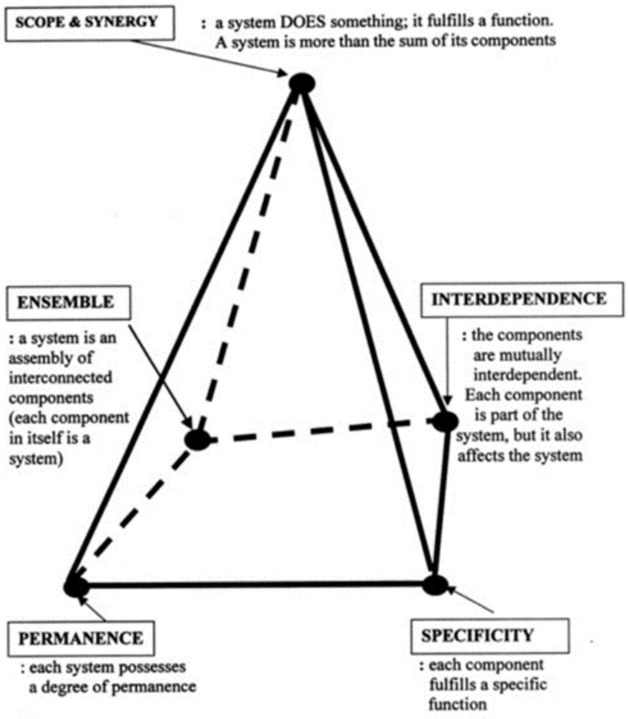

Figure 1: Features of a power system[3]

The power system is made up of the several components. These include generation, transmission, distribution and various protective schemes to ensure reliable and safe operations of the power system.

These protective schemes relate to system operations and are essential to ensuring there is sufficient generation to meet load/demand and that the system is operated in a reliable and safe manner. System operators perform the function of operating the power system and do so within two-time horizons.

- The first-time horizon is the operations horizon where the system operator manages and operates the power system in real-time possibly on a minute by minute, second by second basis or every 5 minutes to ensure the system is operating safely and reliably.
- The second is the planning horizon which is based on a long-term view of the system (typically, 5, 10 or 15 years) to ensure that there is sufficient generation and system capacity to meet load/demand and the system operates in a safe and reliable manner. Both these horizons need to be catered for extensively in the power system and power system operations.

In practical terms, the technical parameters within which the system needs to be operated at to ensure a safe and reliable system are outlined in a document commonly referred to in South

[3]Source: Lecture slides, EEE 4126F – Energy Systems & Grids II

Africa as the Grid code. This document is prepared by the system operator (i.e. Eskom) and approved by the National Energy Regulator of South Africa. It details the manner in which and the bounds within which the power system needs to be operated at to maintain stability of the system. In developing the grid code, the system operator considers the specific characteristics of the transmission and distribution infrastructure in South Africa, the mix of generation sources used to produce electricity as well as several other factors.

2.2 Power system models with and without variable renewable energy

Putting these various components into a model assists in understanding how the power system will work under different circumstances.

2.2.1 Power system model – without Renewable Energy

The figure below illustrates the traditional power system without renewable energy resources. It is an example of a multi-machine power model with four large synchronous generators (G1, G2, G3 and G4). These generators are well- synchronised in the system and they work together in concert to ensure that power is delivered to the load (the green rectangular blocks) in a reliable and safe way such that that the grid code and operational requirements are met well.

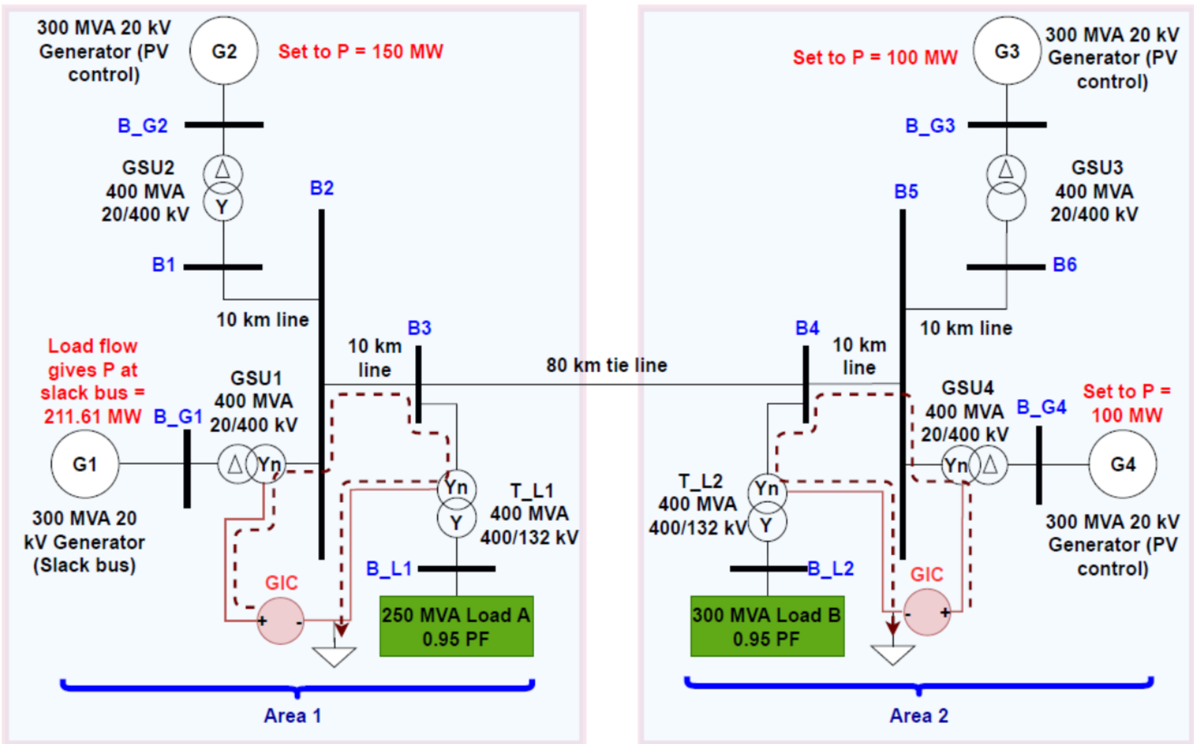

Figure 2: Power system model without renewable energy[4]

[4] P. Jankee, D. T. O. Oyedokun and H. K. Chisepo, Dynamic Response of Power Systems With Real GICs: Impact on Generator Excitation Control," in IEEE Transactions on Power Delivery, vol. 37, no. 6, pp. 4911-4922, Dec. 2022, doi: 10.1109/TPWRD.2022.3162881

2.2.2 Power system model with variable renewable energy

The figure below illustrates a power system where there are wind farms located as indicated by the red X and an 80-kilometer transmission line is used to transmit power from one area of the network to the other. Generally, the transmission infrastructure to evacuate power is limited and there are certain constraints which need to be considered and planned for in the short to medium term to ensure a high penetration of VRE.

In a power system where there is increasing VRE penetration such as South Africa, these changes in the generation mix introduce complexities which need to be accounted for within the system. The key challenge for power system operations where there is a high penetration of VRE is the variability of energy produced by these resources. This is not necessarily the case with other renewable energy sources such as hydro and biomass.

One of the other challenges with VRE is that these resources may not be located close to load centres. Therefore the transmission network in these areas needs to be able to evacuate the power generated from these areas to where load centres. This is particularly a challenge for South Africa where some of the best VRE resources are located in the Northern Cape where there is no longer capacity available on transmission network to evacuate power to load centres.

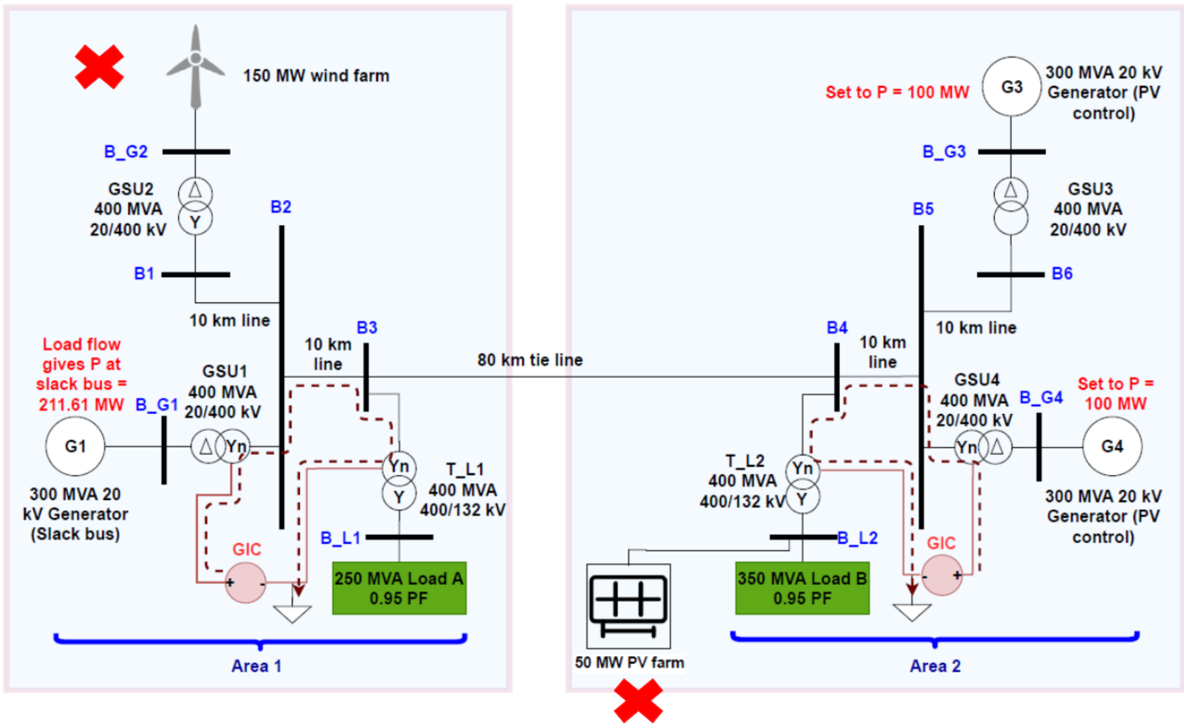

Figure 3: Power system model with variable renewable energy[5]

2.3 Power system frequency, stability, quality, and reliability

For the power system to be operated safely and reliably, several concepts need to considered and monitored by the system operator. These concepts are power system frequency, stability, quality, and reliability. Each of these are discussed in more detail below.

[5] Source: Adapted from P. Jankee, D. T. O. Oyedokun and H. K. Chisepo, "Dynamic Response of Power Systems With Real GICs: Impact on Generator Excitation Control," in IEEE Transactions on Power Delivery, vol. 37, no. 6, pp. 4911-4922, Dec. 2022, doi: 10.1109/TPWRD.2022.3162881

2.3.1 Power system stability

Another concept in power system operations is power system stability. Maintaining power system stability entails the achievement of a few fundamental objectives:

- Keep the lights on – There needs to be sufficient generation to meet load/demand;
- Keep them bright enough – There needs to sufficient energy to fully illuminate the light bulb;
- Keep them steady – There must be no variation in the voltage or in simple terms, no flickering; and
- Reliably ride through contingencies – The system needs to be able to respond to disturbances with minimal disruption to operating parameters/bounds.

A generally accepted technical definition of power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact.[6]

Power system stability can be classified into several aspects including resonance stability, converter-driven stability, rotor angle stability, voltage stability and frequency stability. Of key importance within the context of the increasing penetration of VRE is its impact on the stability of power system frequency. The grid code would define the bounds within which the power system needs to be operated at to maintain stability of the power system.

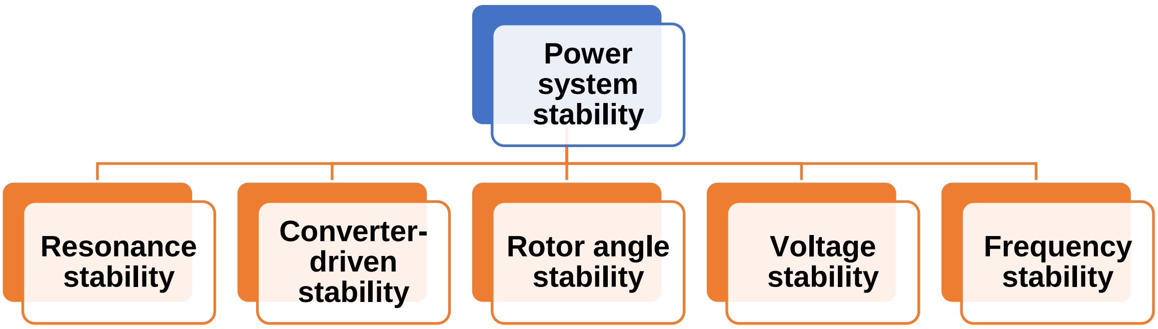

Figure 4: Classification of power system stability[7]

The variability of energy produced by renewable energy sources such as solar and wind requires system operators to manage power system frequency more carefully as the penetration of VRE increases. Frequency within the context of a power system is a parameter that has no physical existence. It is a property of electricity current and voltage signal. It can be measured, in general definition terms, by the number of cycles in one second and the unit is in Hertz (Hz).

In the context of a power system, frequency of the system provides a good indication of how well load and generation are balanced. A continuous balance needs to be maintained in the system as load may increase (switching on a light anywhere in the system) or decrease

[6] [7] N. Hatziargyriou et al., "Definition and Classification of Power System Stability – Revisited & Extended," in IEEE Transactions on Power Systems, vol. 36, no. 4, pp. 3271-3281, July 2021, doi: 10.1109/TPWRS.2020.3041774.

[7] *Source: N. Hatziargyriou et al., "Definition and Classification of Power System Stability – Revisited & Extended," in IEEE Transactions on Power Systems, vol. 36, no. 4, pp. 3271-3281, July 2021, doi: 10.1109/TPWRS.2020.3041774*

(putting a light off anywhere in the system) requiring a similar increase or decrease in electricity generation somewhere in the system to match the change in load.

As mentioned earlier, for the power system to be stable it needs to be able to reliably deal with contingencies. For example, if there is a sudden loss in generation capacity such as a unit tripping, the frequency of the power system will fall. In a traditional power system dominated by synchronous generation, these generators will respond to the fall in frequency and provide inertia to the system (i.e. additional energy) such that the frequency of the power system recovers within a short period of time (5 to 10 minutes) – as shown in the figure below.

However, VRE generating resources are unable to respond to a fall in frequency of the system in the same way as synchronous generators. Therefore, it is a greater challenge to maintain power system frequency stability with the increasing penetration of VER.

Another complexity in maintaining frequency stability of the power system where there is higher penetration of VRE is the mis-match between the generation profile of VRE resources and the load profile. A simple example – solar power peaks during the mid-day, low in the morning and evening, when we don’t have solar power, how do we meet demand where solar is not available. Other renewable resources such as wind, battery storage and non-renewable resources such as coal can be used to meet the load profile when the solar generation is not available.

2.3.2 Power quality

Power quality is a measure of the electrical current and voltage relative to the ideal or expected conditions. Electrical voltage is the electromotive force between two points in an electrical circuit. Electric current refers to the flow of electrons through a conducting material which in a power system are the electrical wires in the system. Finally, this is linked to electrical power which is the rate at which electrical energy is consumed.

Power systems need to be operated within specified bounds of these parameters to ensure safe and reliable operation of the system. These bounds will be specified in the grid code. Differences between the actual and expected conditions may be caused by the voltage level, spikes in voltage, variations in the voltage, voltage dips and sags as well as harmonic distortions. Several events may cause these differences including overloads, insufficient reactive power support, protection malfunctions, harmonics, network inadequacy, among others. The impact of poor power quality is the potential for damage to both system and consumer equipment caused by the variable voltage.

2.3.3 Power system reliability

Power system reliability is the ability of the system to perform its intended function. Two important concepts are considered in assessing the reliability of the power system - the adequacy and the security of the system.

When assessing the ***adequacy of the system***, there are four areas that are considered:

1. System adequacy which is the ability of the power system to convert primary fuels into electricity and transfer it to the end-user in a sustainable manner;
2. Generation adequacy is the availability of sufficient generating (and import) capacity to meet demand;
3. Network adequacy implies the adequacy of the transmission, distribution and cross-border interconnections to transmit and deliver electricity to the consumer;

4. Market adequacy refers to the ability of the market to establish and maintain an efficient link between producers and consumers of electricity.

The second concept in power system reliability is the ***security of the system***. It is described as the ability of the power system to withstand a pre-determined set of disturbances. Security of supply is considered under two-time horizons – short-term and long-term. In the short term, the reliability of the power system operation in real-time is monitored and assessed in respect of its response to sudden disturbances and a pre-determined set of disturbances. However, in the long-term, the security of the system is dependent on several factors such as access to primary fuels to generate electricity, the system adequacy and market adequacy.

When assessing the reliability of the South African power system, there is clearly inadequate generation to meet demand and, in some areas, there are network inadequacies.

3. Introduction to power systems: real-world planning

The power system is a complex system that requires several component systems to be interconnected and work harmoniously together at any given point in time to enable it to achieve its function of delivering power. The complexity and interconnectedness of the power system requires extensive planning in both the short- and long-term time horizons. Power system planning requires the technical capabilities of the power system to be coupled with the economics of power supply to assist in decision making across the different time horizons and the potential impact on system operations.

The key concepts discussed below include the generating capability and the cost of generation, system planning and decision-making timelines, dispatch in the short term, reserve types and uses and new services that may be procured by the system operator in future.

3.1 Generating capability and the cost of generation

One of the building blocks of power system planning is generation capability. Different generation technologies have different technical characteristics and economic outcomes which need to be considered when planning the power system. All generation technologies have a different combination of fixed costs (costs that do not change with output) and variable costs (those directly related to output). On the extremes are diesel fired generation and nuclear power. Diesel fired electricity generation has low fixed costs (the capacity is cheap) however it has exceptionally high variable (fuel) costs. Whereas nuclear power has low variable costs (such as fuel and operating and maintenance costs) however it has exceptionally high fixed costs (see Figure 5).

Renewable energy such as solar and wind, generally, has high fixed costs with almost no variable costs (i.e., no fuel costs and only minimal operating and maintenance costs). However, these types of generation are variable and not dispatchable as it is dependent on external factors for generation. Gas fired electricity generation has lower fixed costs (approximately 30% of coal capacity costs) however it has generally higher fuel costs. At lower load factors gas fired generation is preferable to coal however this depends on international gas (and coal) prices.

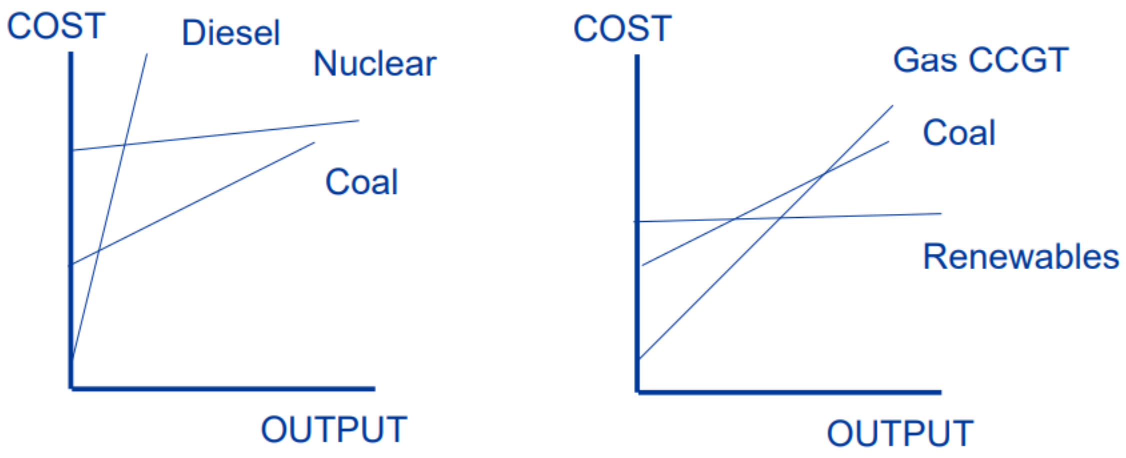

Figure 5: Graphs showing cost of production for diesel, nuclear, gas and renewables

The technical capabilities of each generation technology combined with the economic cost are considered in system planning and operation for example, a renewable energy generator once built is largely a sunk cost with little to no variable cost. Therefore, the objective would be to maximise its output. There is a very limited potential to adjust this output. However, if the renewable energy generator needs to be curtailed, there is an economic cost associated with this lost energy for which the generator needs to be compensated. Therefore, decisions on the generation capacity that should be built need to be carefully considered in light the potential consequences for the power system if that capacity is built.

3.2 Decision-making timelines

There are different time horizons to be considered in system planning (discussed in section 2.1 above). In considering the generation capacity that needs to be built to meet future electricity demand, the decision to build certain generation capacity such as coal or nuclear needs to be made well in advance given the long lead times for building such capacity. However, more flexible generation capacity such as gas the decision to build can be made in a shorter time horizon given the shorter lead times to build this capacity. In the long term, almost all parameters are variable such as what generation capacity should be built and where it should be built.

However, when considering a shorter time horizon of 3 to 5 years, a significant portion of the costs of the system are now fixed. Importantly, in this time horizon, fuel supply for coal, diesel or gas fired generation needs to be secured through contractual arrangements. Another important aspect that needs to be planned is maintenance scheduling and production planning which is usually planned 1 to 2 years in advance. The maintenance schedule needs to be co-ordinated across all generation capacity to ensure that the maximum generation capacity is available at any point in time.

Then, there is the day-ahead time horizon where all costs are to a large extent fixed. Short run marginal costs are used to determine the generation capacity that is to be scheduled and dispatched the following day within technical constraints. Where there are large generators in the system such as coal, a unit commitment decision needs to be made a day in advance, specifying the generating units that will be operating and at what level. Once this decision is made, the schedule is effectively fixed. There may be some flexibility in terms of whether the unit is dispatched or not however this is limited as the generating unit was committed in the schedule and will be operating. For generation capacity that is more flexible such as gas, pumped storage and batteries, there is no need to provide unit commitment a day ahead.

However, when optimising the system consideration is given to the flexible generating capacity to ensure the entire system is optimised.

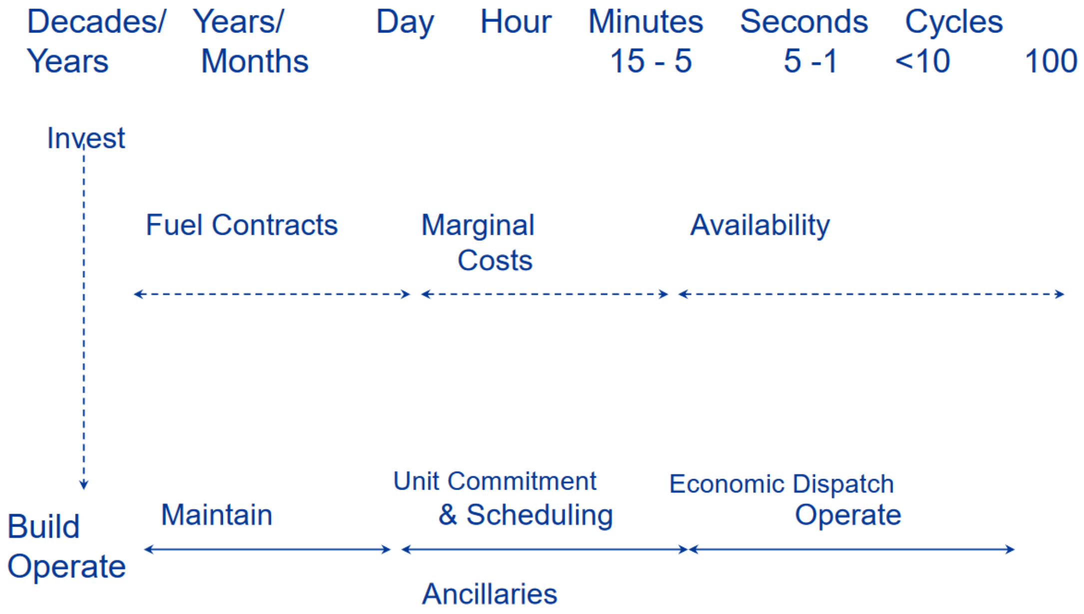

Figure 6: System planning and decision making timelines

In the day-ahead market scheduling and merit order is determined on the basis of short run marginal costs against a demand forecast. The scheduling and merit order is optimised to provide the least cost to meet the demand over a 24-hour period. The costs of various generating units in the schedule are stacked to determine the supply curve (red line labelled S), as shown in the figure below. The supply curve does not start at 0 as some generating units need to be operated at its minimum stable generation point which may be as high as 60% of maximum capacity. Therefore, there might be times during the 24 hours when VER generation such as wind may need to be curtailed as all other generating units are at the minimum generation point and cannot be lowered further. The supply curve may also differ hour by hour depending on technical parameters in terms of the generating capacity that is available and ramping constraints. As such some generating units may be available at the peak but not for other periods during the 24 hours.

The demand curve (blue line labelled D) is set at the forecast demand for the following day. The intersection of the demand and supply curves will determine the schedule for the generating units that will be used and dispatched the following day as well as the price for all the generation to be supplied (the green line in the figure below).

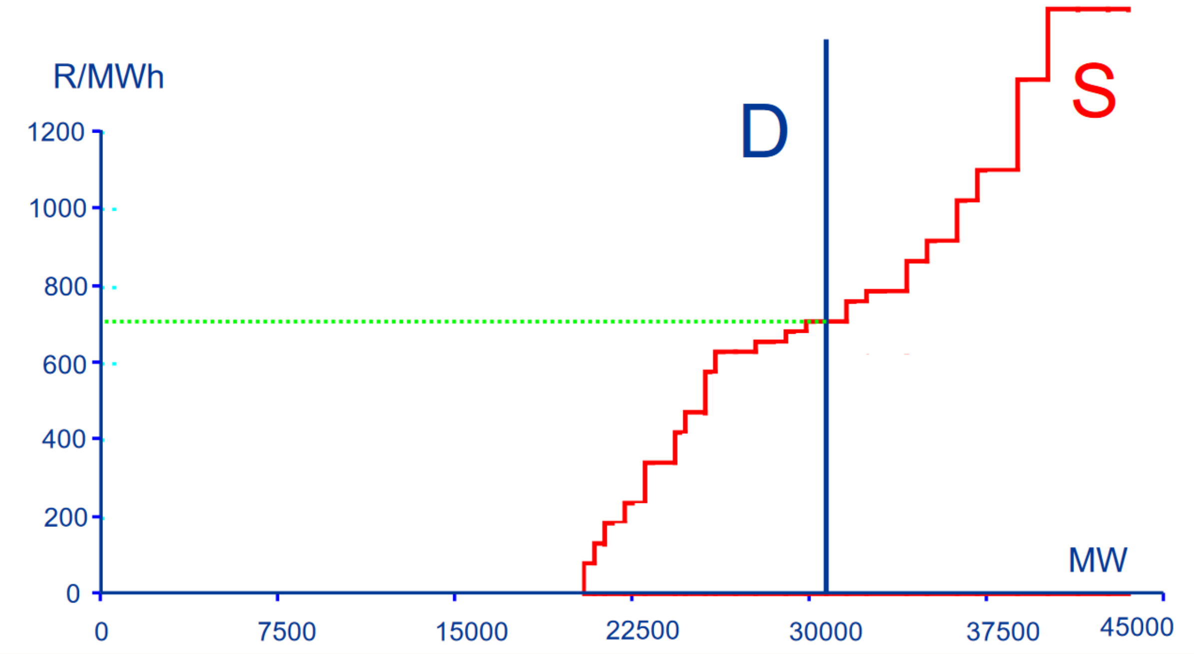

Figure 7: Demand and supply in the day-ahead market

3.3 Reserve types and uses

Generation reserves can be considered as electricity supplies that are currently not been used in the system but is available to be supplied into the system at relatively short notice should there be an unexpected disturbance to the system. It is used to provide or withdraw inertia from the power system to maintain the frequency within the pre-determined bounds for safe and reliable operation of the system. The South African power system is operated at 50Hz with an upper bound of 50.85Hz and a lower bound of 40.85 Hz.

It is a type of ancillary service that is used by system operators to operate the power system safely and reliably conforming to the parameters outlined in the grid code. Currently, there are different types of reserves that are required and used to balance the system:

1. Instantaneous reserve also referred to as primary frequency control is used if the frequency moves outside of the pre-defined bounds within a 10 second period. In South Africa, typically coal-fired generation can respond quickly enough to provide instantaneous reserve. Large electricity users with a demand side managed load can also provide instantaneous reserve where they can lower their demand within 10 seconds to provide inertia to the system. Gas and diesel generation can also provide instantaneous reserve if the units are already running.
2. Regulation reserve is generation capacity that can be ramped up or ramped down within a few seconds in response to a control signal from system operations. It is also sometimes referred to as automatic generation control or secondary and tertiary frequency control. In South Africa, several different coal fired generators are used to provide regulation reserve which enables a faster response to the control signal. Gas and diesel generation can also provide regulation reserve if the units are already running.
3. 10-minute reserve is generating capacity that can respond to a control signal from system operations within a 10-minute time frame. Pumped storage and coal-fired generation is often used to provide the 10-minute reserve. This reserve can also be

used to restore instantaneous and regulation reserve in the event of a second or third disturbance to the system.

4. Supplemental reserve is generating capacity that is not currently connected to the grid but can be brought online within a short timeframe of less than 6 hours and be available for around one to two hours.
5. Emergency reserve is generating capacity that can respond to a system frequency disturbance in 10 seconds and must be fully available within 10 minutes. Large users with interruptible supply may also provide the emergency reserve.

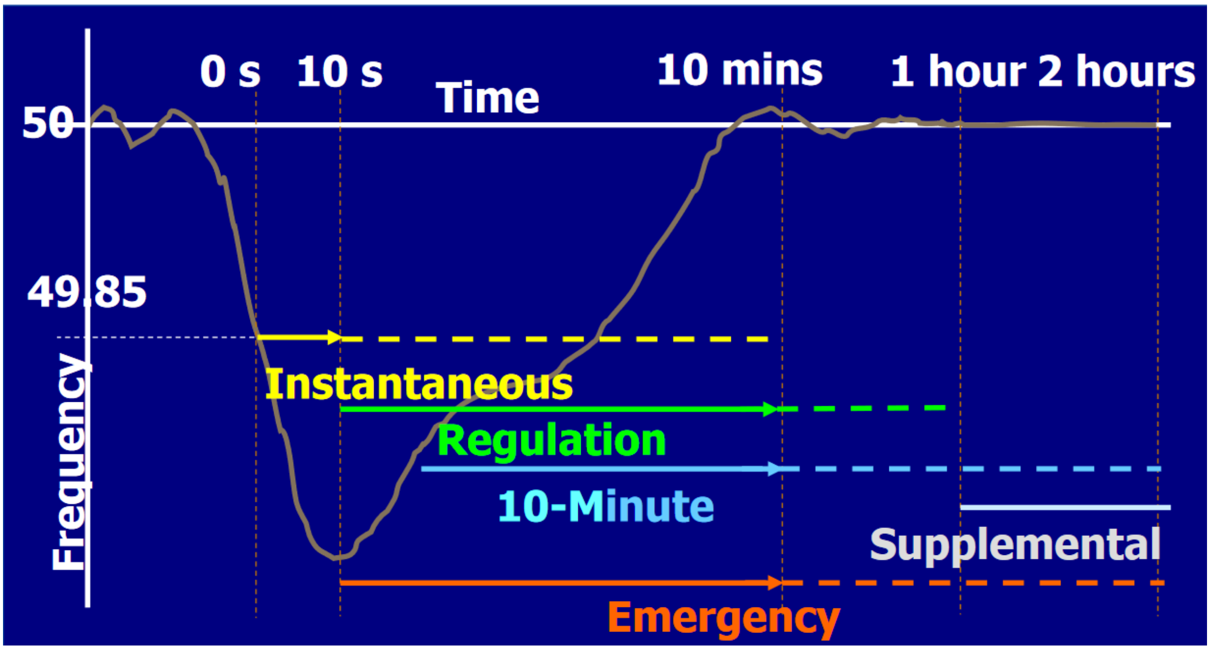

Figure 8: Use of reserves for power system frequency stability

With the increased penetration of variable renewable energy, the new focus for system operations is on frequency movement in both directions. It seems to be the case that the probability of over-supply of energy from renewable generation is approaching that of the probability of under-supply. Where there is over-supply, this will increase the frequency of the system, as shown in the figure below. As a result, reserves may be required to reduce generation. This can be problematic where there are inflexible generating units in the system with minimum generation points for safe operations.

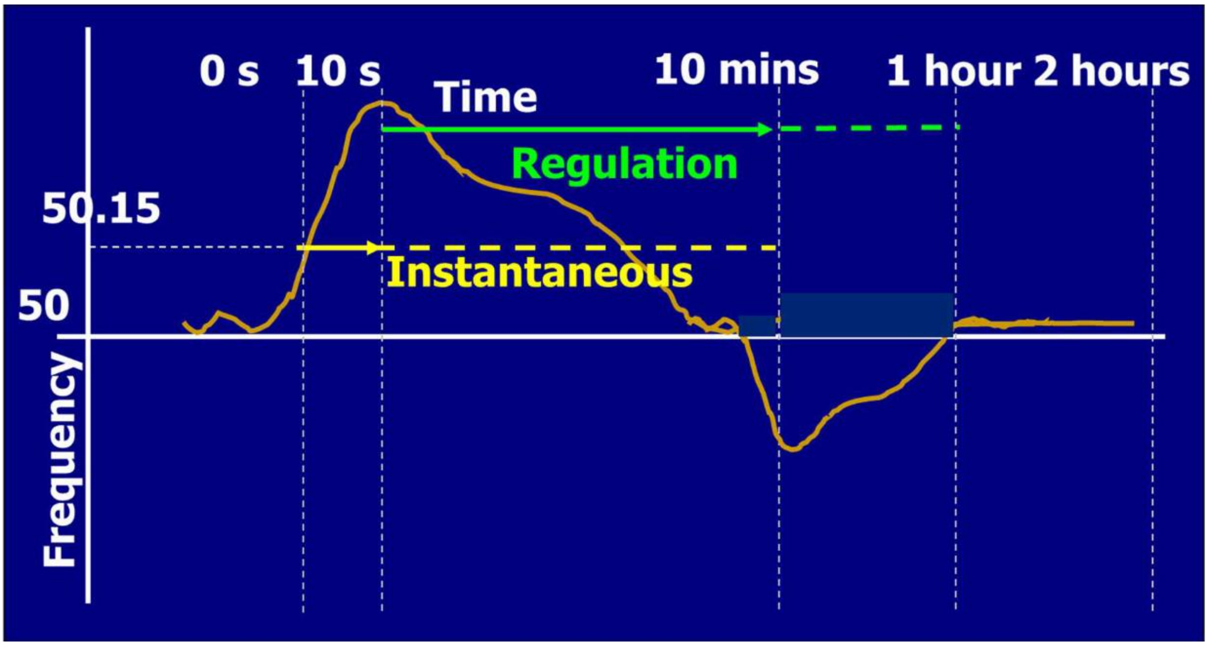

Figure 9: Ancillary services and fast response

3.4 New services that may be procured by the system operator in future

New types of services may be required to respond to the challenges posed by the increased penetration of VRE to the safe and reliable operation of the power system.

The cheapest potential energy source currently is renewable energy (either wind or solar PV generation). An energy only market will tend to favour wind and solar PV generation however the energy profile does not often match the consumption patterns or load profile. Therefore, generating capacity such as gas or battery storage may be required in future to supply the residual demand. However, the investment in such generation technologies may be not justified if it were to compete against renewable energy on the basis on only supplying energy. Therefore, in future a type of capacity market for the capacity to supply the residual demand may be required.

Another challenge to the increased penetration of the VRE is the current constraints of the transmission infrastructure. Congestion management of the transmission network is therefore critical to ensure safe and reliable transmission of power. The system operator may require day-ahead and real-time monitoring of the transmission network. Understanding the constraints of the transmission network may imply different approaches to transmission tariff design such as separate transmission tariffs for different geographic areas may be required in the future.