Voltage Stability Challenges & Opportunities in SA's Weak Grids

The Role of Hybrid Energy Systems

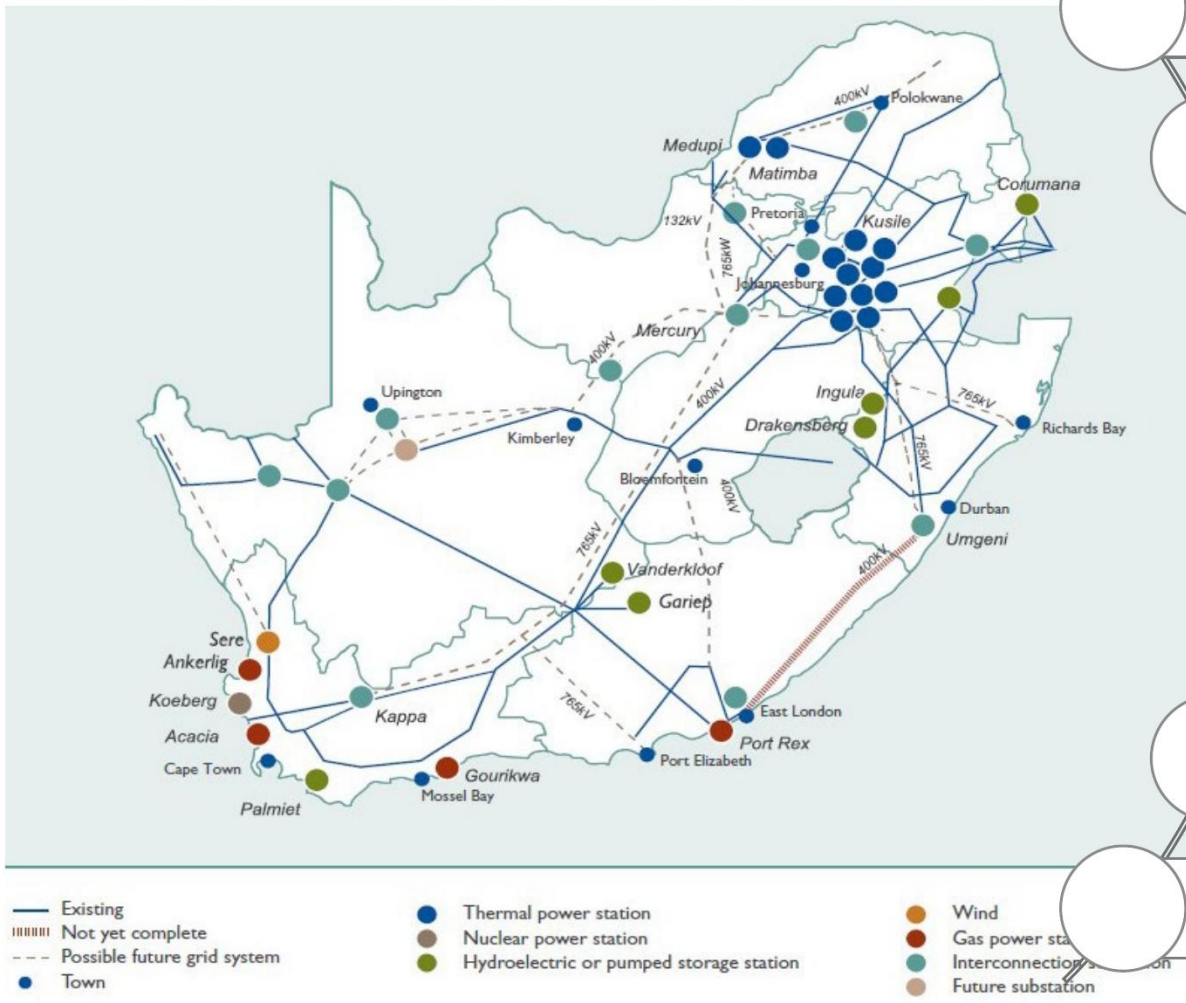
7 October 2026



Naniki Nzuza

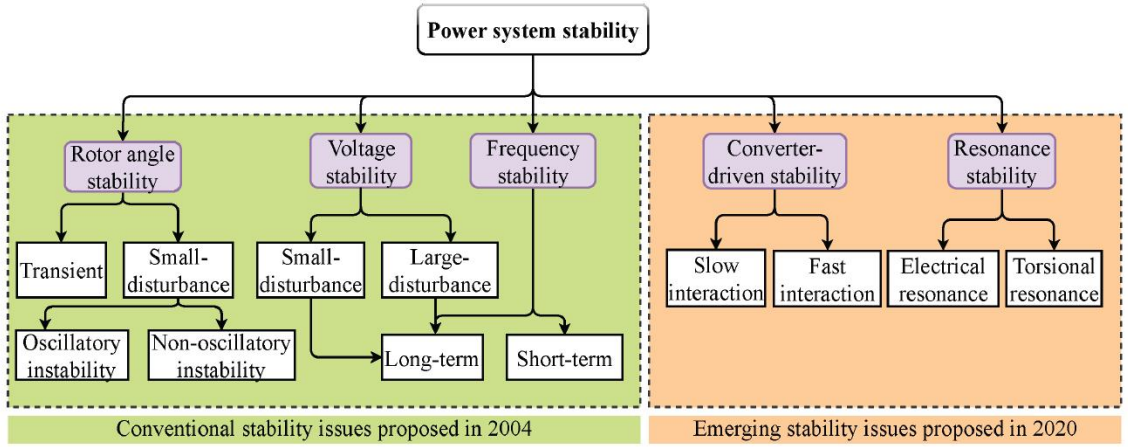
Principal Grid Engineer – Mainstream Renewable Power SA

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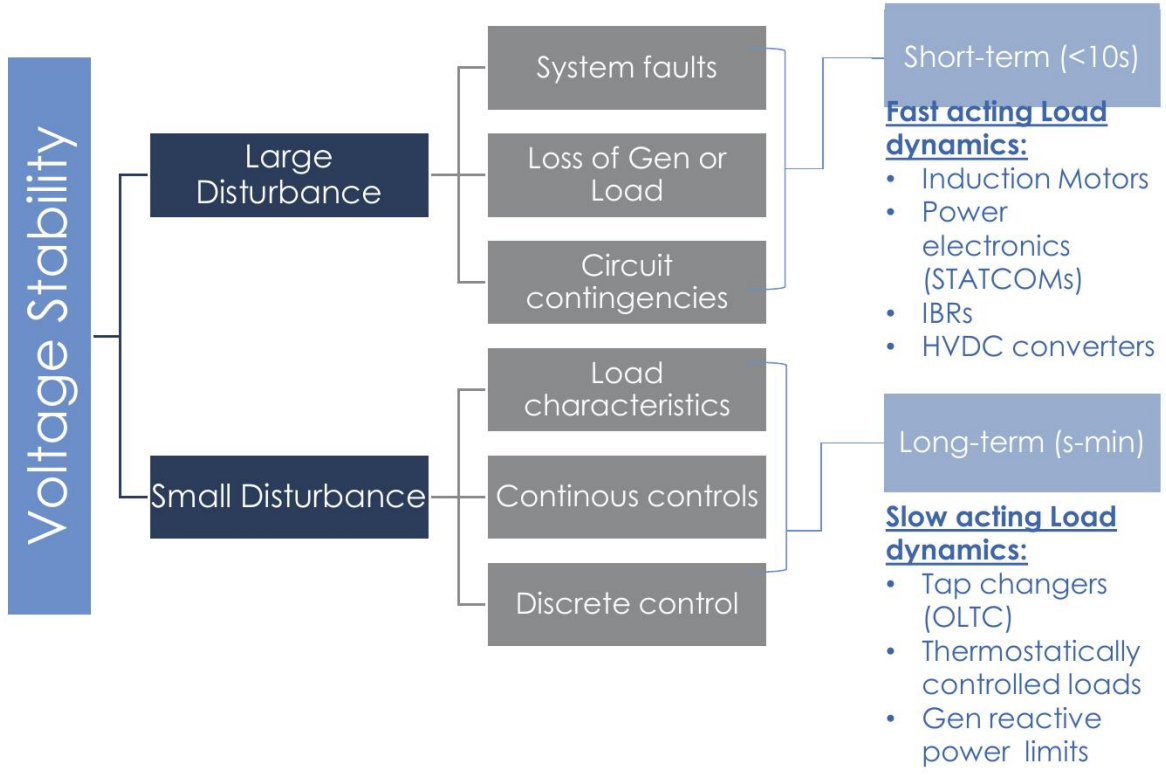


1. Power System Classification
2. Voltage Stability
3. Weak Grids
4. Hybrid Renewable Generation
5. Modified IEEE 14 Bus System
6. Simulation Results
7. Conclusion & Future Work

Power System Stability Classification



"The ability of the Power System, for a given initial operating condition, to regain state of equilibrium after a disturbance with most variable bounded such that the entire system remain intact."



Rotor Angle
Synchronism after faults (3-5s)

Voltage
Steady Voltages at all buses

Frequency
System Frequency recovery

Shair, J. et al. Power System Stability issues, classifications and research prospects in high penetration of RE and power electronics.2021, IEEE/CIGRE Joint Task Force. June 2003

Weak Grids & Northern Cape Challenge

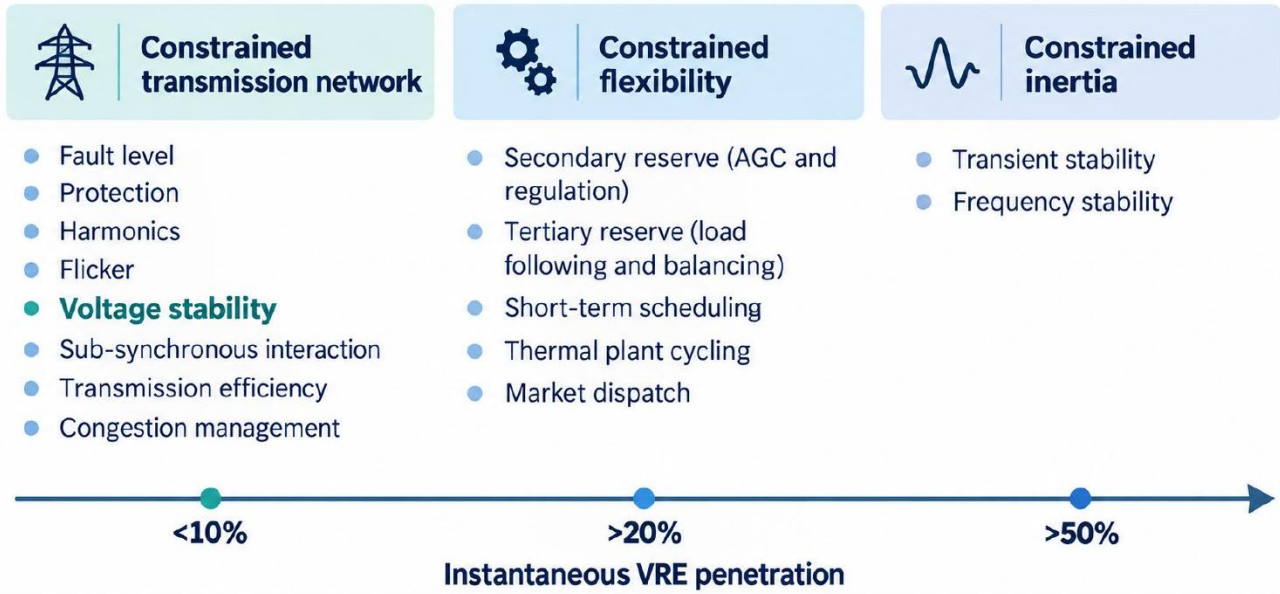
Low short-circuit capacity
Fault detection and protection coordination become challenging

Vulnerable to control Interactions
IBRs can interact negatively with grid causing oscillations/instability

Limited Voltage Regulation capability
Challenges in maintaining voltages within regulated voltage bands during faults

Reduced System Inertia
Fewer synchronous generators affect frequency control

Grid integration challenges as VRE penetration increases



Short-circuit Ratio:

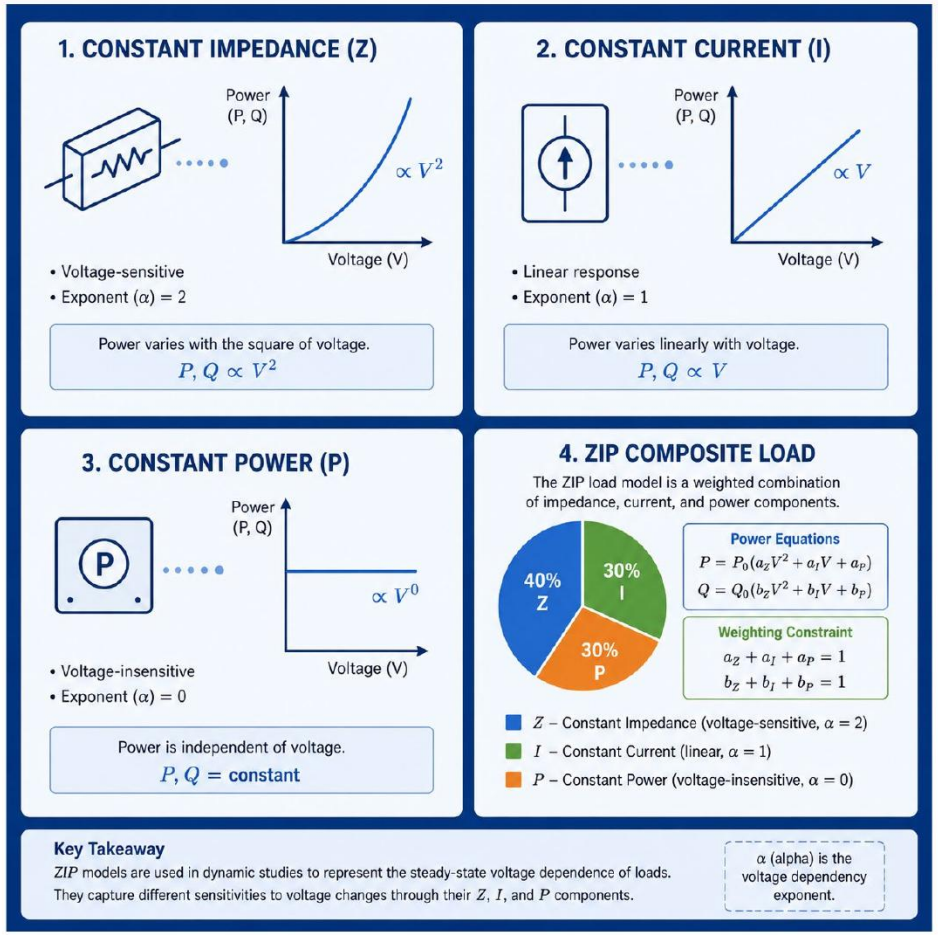
$$SCR = SCC/P_{IBR}$$

SCC - the short-circuit capacity assuming a three-phase fault.

P_{IBR} - the nominal power of the connected IBR.

Boriric',A. et al. System Strength: Classification, evaluation methods and emerging challenges in IBR-dominated grids. 2022 IEEE PES

Dynamic Loads Impact on Voltage Stability



$$P = P_0\,[p_1\overline{V^2} + p_2\bar{V} + p_3]$$
$$Q = Q_0\,[q_1\overline{V^2} + q_2\overline{V^2} + q_3]$$

Static Loads
- ZIP
- Exponential models

Dynamic Loads
- Dynamic exponential recovery load
- Composite load models

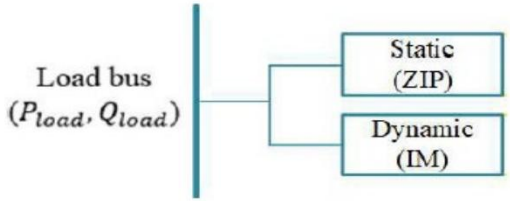
ZIP model (Polynomial) – combines constant-imp (Z), constant-current (I) and constant-power (P)

Polykarpou, E. et al. Effect of Load Composition on Frequency Response of Cyprus Power System. 2018 IEEE Internation Conference on Science of Elec Engineering in Israel

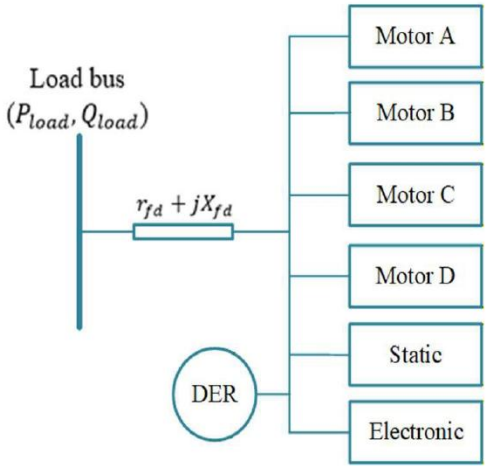
Load Modelling Impacts

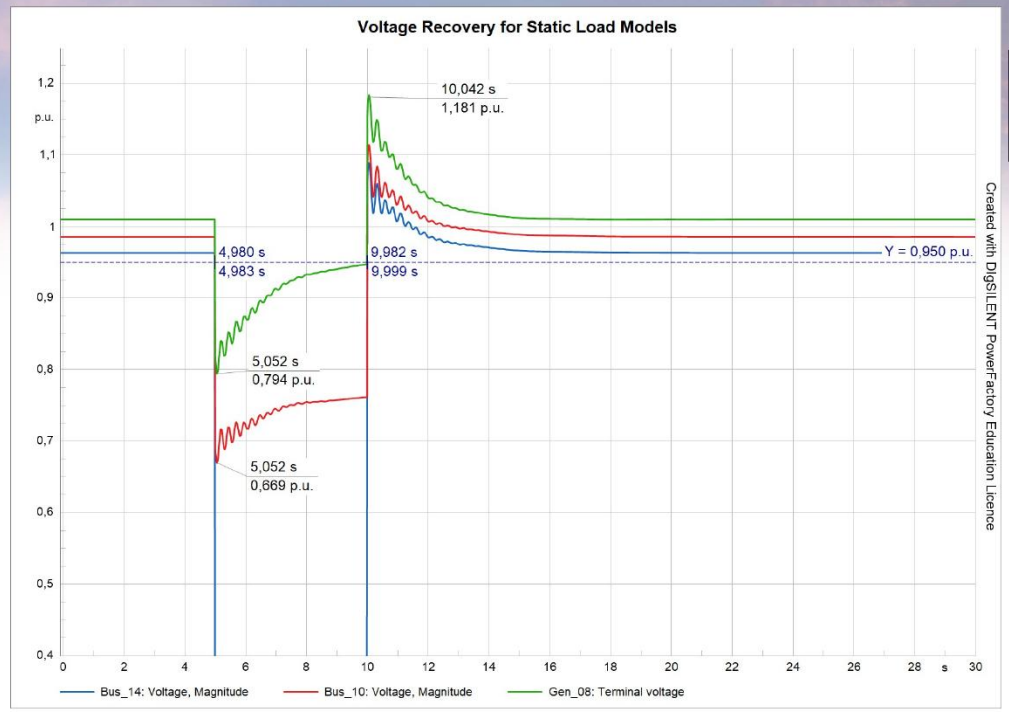
Feature	General Load	Complex Load	WECC Load
Static ZIP	Yes	Yes	Yes
Voltage Dependency	Yes	Yes	Yes
Time Dynamics	No	Limited	Yes
Motor Behaviour	No	No	Yes
Fault Recovery	No	Moderate	Yes

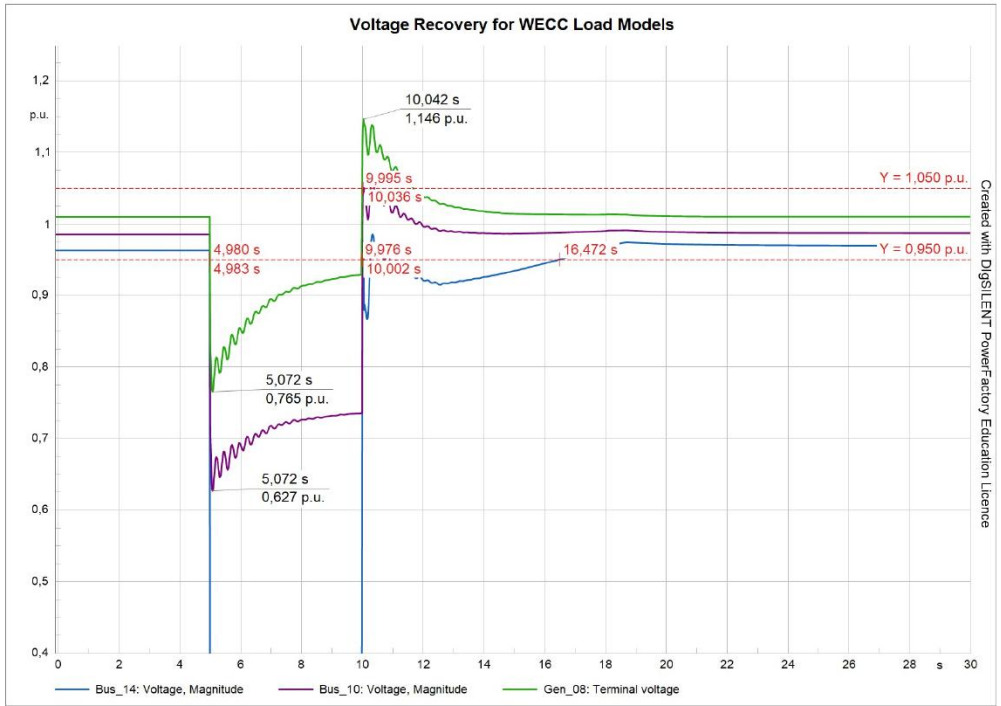
ZIP Loads – Composite or Complex Load model



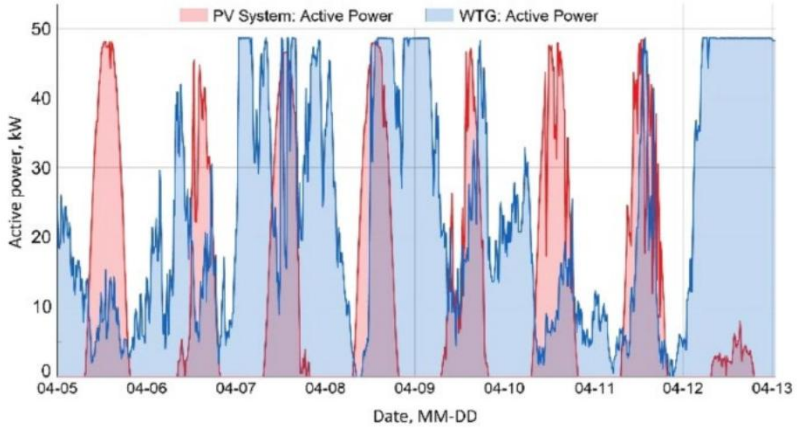
WECC Loads – Widely used by utilities. Residential and commercial loads

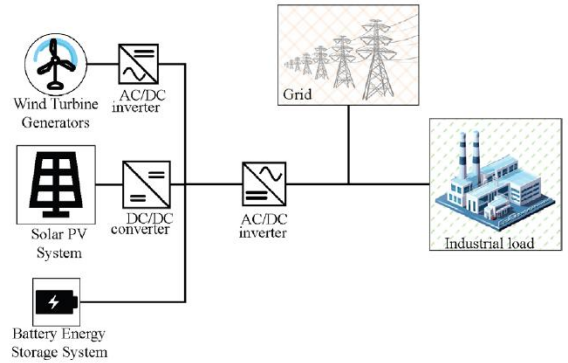






Hybrid Renewable Generation Plants





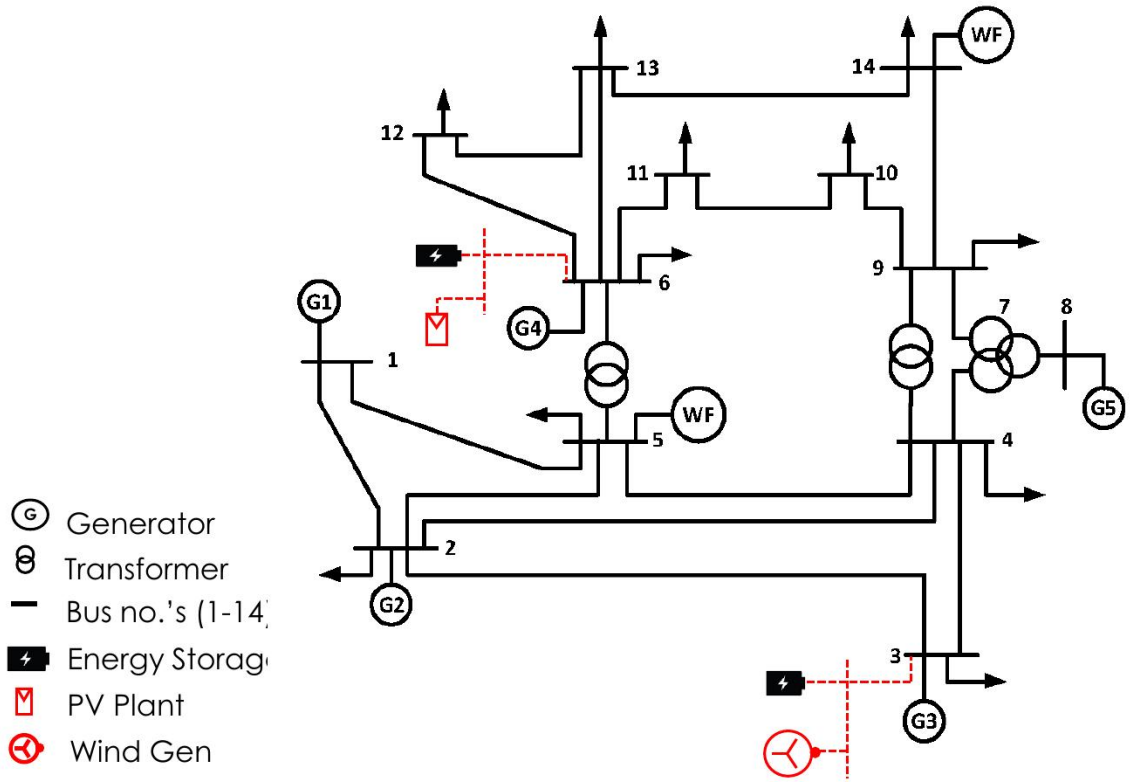
Single Source RE Plants

- Intermittent output
- Non-dispatchable power
- **PV** dependent on irradiance and diurnal cycles
- **Wind** varies local wind speeds

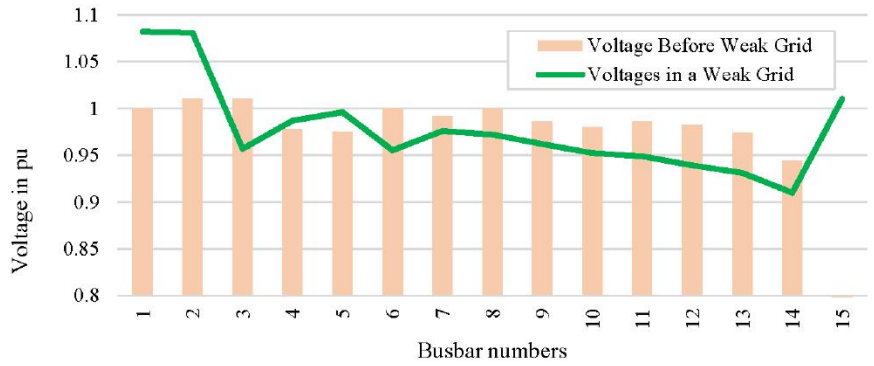
Hybrid RE Plants

- **Improved Stability** – complementary PV/Wind patterns reducing intermittency
- **Grid support** – manage peak generation, provide ancillary support
- **Reduced Curtailment** – excess generation stored and dispatched later
- **Infrastructure Optimization** – defer investments, scalable and modular

IEEE 14 Bus Study Network



- **IEEE 14 Bus system** (14 buses, 2 synchronous Gens, 3 synchronous condensers, 20 lines), modified to emulate a **weak** Northern Cape Grid
  - **External Grid:** Power transfer from strong source e.g. from Mpumalanga
  - **Long Transmission Line:** 215km (Typical Eskom 132kV Dinosaur conductor characteristics, Z)
  - **Lines scaled** Raise reactance and capacitance (Capacitive);
    - Line_1 to 5: X × 1.8, C × 1.5.
    - Line_2 to 3: X × 1.6, C × 1.4.
    - Line_2 to 4: X × 1.4, C × 1.3.



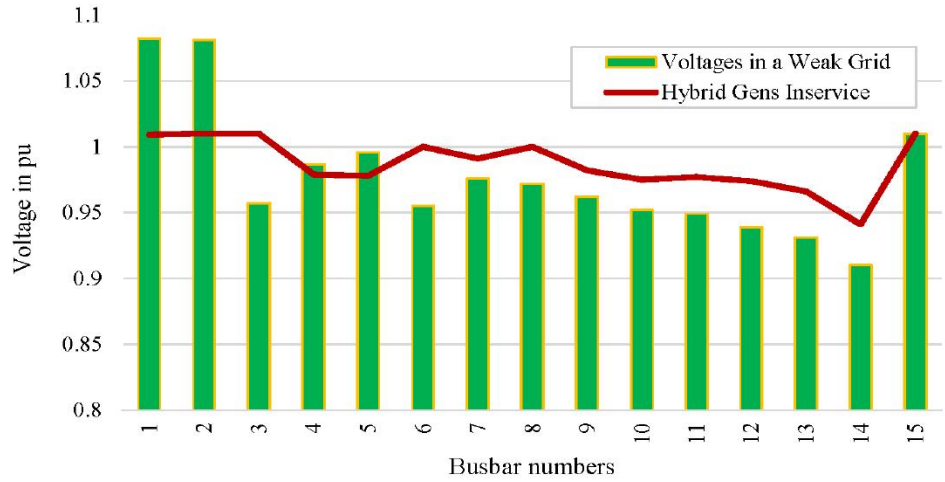
Integrating Hybrid Renewable Generation Plants

Bus 6

- **PV Plant:** S_{rated} = 30MVA (P_{max} = 30MW)
- **Battery Energy Storage:** S_{rated} = 15MVA, (E = 30MWh)

Bus 3

- **Wind Plant:** S_{rated} = 40MVA (P_{max} = 30MW)
- **Battery Energy Storage:** S_{rated} = 10MVA, (E = 20MWh



Busbar	01	02	04	05	06	08	09	12	13	14
Sk" [MVA]	2810,2	1588,2	583,2	662	457,7	374,6	408,3	243,9	316,8	133,3
IBR = 45	62,45	35,29	12,96	14,71	10,17	8,32	9,07	5,42	7,04	2,96

- **Bus 6** represents a weak, high-impedance node; **Bus 3** is a major load/generation aggregation point.

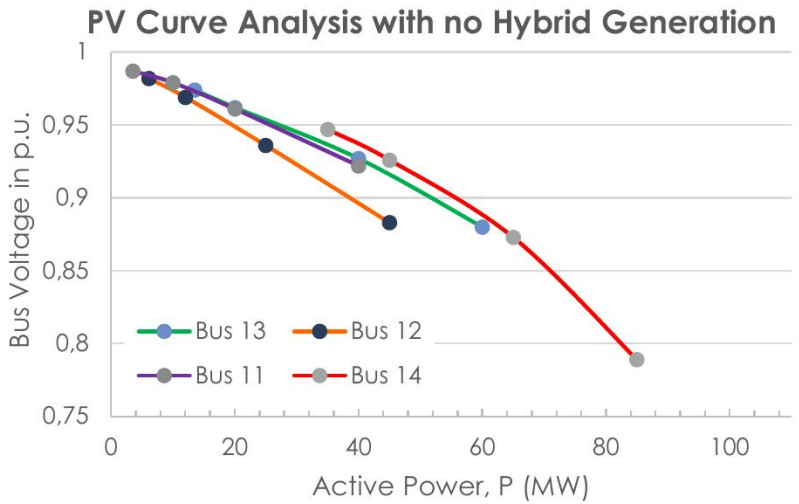
SCR > 10 Strong Grid

3 < SCR < 10 Moderate strength

SCR < 3 Weak Grid

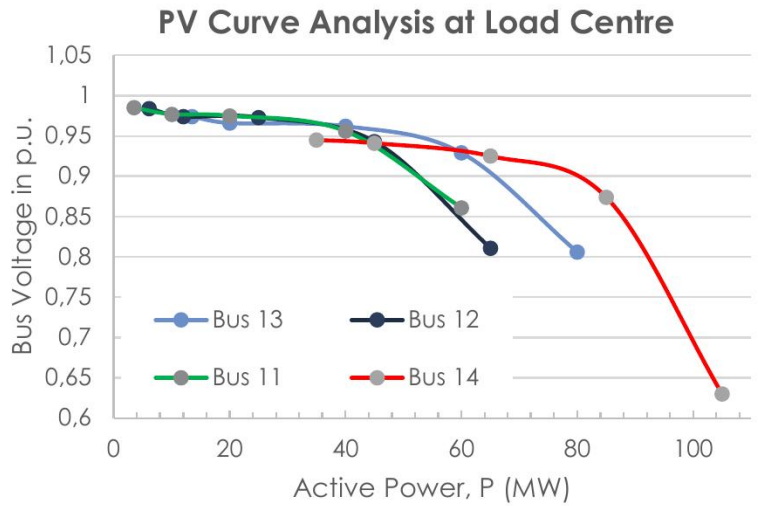
Simulation Results

- Voltage sensitivity tested with gradual load increases (~ 20 MW steps) until instability.
- P-V and Q-V curves provide reliable steady-state evaluation of proximity to voltage collapse.



Without Hybrid Generation

With Hybrid Generation



Significant Q losses & capacitive over-voltages on long lightly loaded

Distinct overall voltage profile improvement

Conclusions & Future Work



1. **Weak Grid Vulnerabilities confirmed**
   Low SCR areas with IBR penetration exacerbate voltage control difficulties and reactive power deficits

2. **Hybrid + BESS = Promising Solution**
   Optimally designed hybrid systems with storage can support grid stability and mitigate voltage instability.

3. **Proactive Planning is Essential**
   Accurate dynamic modelling and grid code compliance are critical for reliable integration.

4. **Future Work**
   Refined dynamic modelling of 14-bus system, real-time monitoring (PMU/WMU) and OEM collaboration for electromagnetic transient studies.

THANK YOU

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