Adaptive OOS protection scheme to enhance rotor stability of the system

Nande Fose, Senthil Krishnamurthy, and Prathaban Moodley*
Department of Electrical, Electronics and Computer Engineering
Cape Peninsula University of Technology, PO BOX 1906, Bellville 7535, South Africa
*South African National Energy Development Institute (SANEDI), Upper Grayston Office Park, Sandton, 2146
nandetillax@gmail.com, krishnamurthys@cput.ac.za and prathabanm@sanedi.org.za

2024 32nd Southern African Universities Power Engineering Conference (SAUPEC) | 979-8-3503-7134-5/24/$31.00 ©2024 IEEE | DOI: 10.1109/SAUPEC60914.2024.10445082

Abstract—
The impact of large-scale deployment of Renewable Energy Sources, especially inverter-connected wind turbines and photovoltaics, on the variability of RES generation shares globally. This is a critical point as it emphasizes the transition from conventional generators to RES, which lack rotational inertia. The usual assumption of high grid inertia with minor variations is no longer valid in power networks with significant RES shares. This is crucial, as it sets the stage for understanding the subsequent challenges related to frequency dynamics and power system stability. The lack of rotational inertia in RES-connected devices affects frequency dynamics and power system stability. Understanding and addressing these issues are essential for ensuring the reliability and security of power systems with a substantial share of RES. The key contribution of the research work is in the area of Out-of-Step (OOS) protection systems. This system becomes particularly important in handling unpredictable contingencies and preventing angular instability that could lead to blackouts. Identifying and isolating unstable swings after disruptions is a significant advancement in power system stability. The development of a framework to investigate power system rotor angle stability during steady state and transient stability occurrences using DIgSILENT PowerFactory® software. The application of the proposed protection scheme on the modified Eskom transmission network is a practical demonstration of its applicability. A critical aspect of power systems ensuring stability in the face of increasing RES penetration. The focus on Out-of-Step protection systems, along with the application on a real-world transmission network, adds practical significance to the research. This work is valuable for ensuring the reliability and resilience of power systems undergoing a transition to higher levels of renewable energy integration.

Keywords—Power System Stability, Out-of-step protection, Dynamic stability, Rotor angle

I. Introduction

During stationary operation, the power grid is often exposed to numerous disturbances that lead to voltage instability. Given the high prevalence of intermittent RERs, their low inertia contribution is an essential and critical feature of rotating synchronous generators, which represents an important property of system dynamics and stability. Systems engineers and developers seek to design the most robust power system structure that can handle all potential eventualities. However, there is a small risk of unforeseen events, where an unexpected scenario of complex events can contribute to the instability of the energy system. As a regime out of sync, angular instability is one of the most dangerous states of instability in the power structure. Due to the limited capacity of transmission lines, short circuits, and lack of generation, the generated power cannot be successfully transmitted to the load. Then, in response to the imbalance between generation and load, some parts of the grid generator continue to operate asynchronously with the rest of the system.

The out-of-step condition cannot be maintained for a long period as it may harm the power system equipment and its integrity. The last resort to prevent the failure of a potential power grid is controlled blackouts on many electrically isolated islands. This division aims to maintain balance within each island [1]. Originally, energy systems were designed to transmit electricity to locations geographically close to power plants. This feature made energy systems very stable, meaning that energy systems operated well beyond their stability limits. A small or significant disruption would not disrupt the system or affect the ability to generate electricity. As the use of electrical energy became more widespread in the early 20th century, the need to transmit energy over long distances became essential. This, along with the increase in network size, has changed the way energy systems operate. Power grids are now forced to operate closer to their reliability limits. The higher the energy demand, the higher the increase in production, and the lack of new transmission lines has caused the system to experience stress conditions and collapse more frequently [2]. Government authorities have imposed restrictions on utilities and grid operators to comply with regulations intended to ensure the reliable operation of the major power grid. This is one of the reasons why network control and security has become an important area of research in recent years. New innovative and more precise protection philosophies and operational guidelines are being applied around the network to maintain system integrity.

The generator rotor speed has a significant contribution to the apparent power supplied by the synchronous machine to the power system. The key question to be answered is how the rotor angle varies in response to a change in power output because under normal stable operation, the rotor angle does not change: The primary considerations in rotor angle stability studies are to ensure that synchronous generators are in synchronism, that all generators' electrical speeds are similar, and that appropriate damping is available if oscillation occurs. [1].

In this paper, an adaptive out-of-step protection scheme for a dynamic stability system is presented. This scheme uses locally installed IEDs to collect at the Palmiet Pump storage generating station busbar. The IEDS for main and back-up backup protection are configured to measure system phasor values. If the angles seen by the devices surpass a pre-defined value, the IED will decide that there’s an out-of-step-condition and thereby triggering the relevant circuit breaker while the non-defective parallel generator continues to supply the load maintaining system integrity. It is important to note the impact of unstable power swings on the remote generating units as the electric center shifts due to inertia.

II. Development of the Proposed Algorithm

The rotor angle stability in literature [2] has been examined to be the ability to maintain the synchronism of interconnected generators both the mechanical torque and the electromagnetic torque of these generators are kept constant. This stability problem is concerned with the electromechanical oscillations in a power system. Transient stability is an important factor when rotor angle stability is concerned as it can produce considerable changes in rotor speeds in response to large disturbances. The swing equation of the power system can be derived as follows:

$$\frac{2H}{\omega_0}\frac{d^2\delta}{dt^2} = P_m - P_e \qquad (1)$$

Where;

H is the inertia constant,
ω_0 is the angular velocity of the machine,
δ Is rotor angle,
P_m is the mechanical power,
P_e is electrical power

The inertia constant of a synchronous machine varies based on its size, which can be large or tiny. Even the inertia constant may vary depending on what material is utilized.

The inertia constant (H) can be calculated as:

$$H = \frac{0.5 \cdot J \cdot \omega_{m0}^2}{S} \qquad (2)$$

Where;
J is total inertia of rotor and turbine,
ω_{m0} is mechanical angular velocity,
S is total power (MVA) of the machine

Measuring fluctuations in system impedance aids in detecting an Out-of-Step problem and creating OOS protection strategies. These schemes' settings are crucial to system reliability and stability. The schemes must be configured to immediately isolate a machine, not just to minimize harm but also to keep instability from spreading to other parts of the system. In the proposed algorithm, in order to prevent network instability, the protection relays continuously measure and validate system vectors to compute angular difference and further issue a trip to isolate the faulted system if the difference precedes the threshold value. By removing such a generator from a system, the network can retrieve the balance of generation and consumption following a disturbance by pushing more percentage loading on the remaining system generators. The flow chart of the proposed method is presented in Fig 1 below:

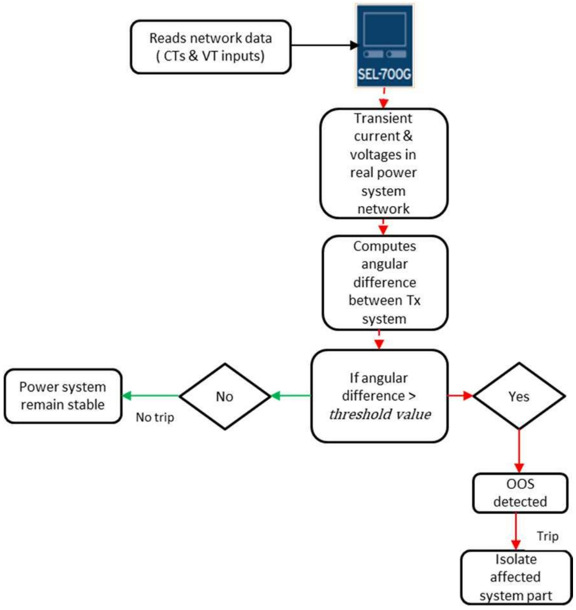


Fig 1. Flow chart of the proposed OOS algorithm

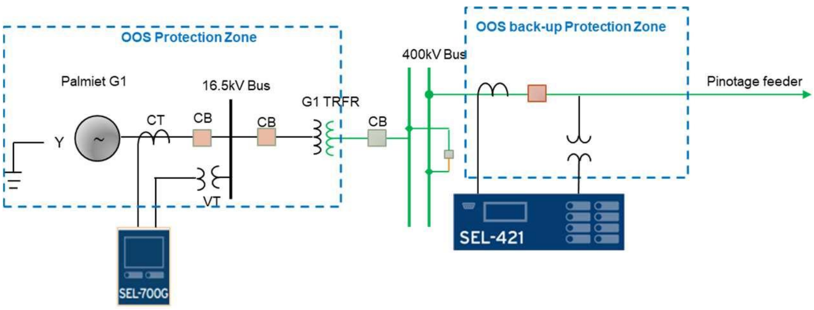
In Fig 1 the signals from the SEL700G relay are Transient current and voltage waveforms similar to the ones that the relay would be exposed to in a real network

In the literature, it is mentioned that generators can be operated in two modes: lock mode and free mode. The generators produce power based on the rotational speed of the prime mover when in lock mode. The generator's operation in free mode is determined by the mechanical torque applied to it. The angular velocity of the generator, which is one of the principal parameters in a prime mover that varies with time when the generators are loaded is paramount. With this said, the rotor angle stability becomes an important property in maintaining the reliability of the system dynamics, thus Out-of-step protection becomes an important feature in such instances.

III. Out-of-step Protection Configuration

It is crucial to explore the framework of relaying for synchronous generators when interfaced with the power system. This section presents a detailed settings analysis/calculations of both relays used in the study for main and backup protection as depicted in Fig 2 below.

Fig 2. 400kV Tx system with the protection schemes optimally placed



A. Main Protection settings

SEL700G IED contains an out-of-step element to detect out-of-step conditions between two or more electrical sources. It is critical to detect and isolate an out-of-step condition as soon as possible because the resulting high peak currents, winding stresses, and shaft torques can be extremely damaging to the generator and the associated generator step-up transformer. The device implements two tripping schemes: Single and double blinder schemes. However, for this paper, a double-blinder scheme will be applied for compact protection against system dynamics.

System equipment parameters need to be known to calculate the response of the IED optimal placed in the system. Moreover, the OOS tripping zone ought to reach the high-side bushings of the generator step-up transformer from the generator neutral [3].

TABLE I. PALMIET GENERATOR DESIGN SPECIFICATIONS

Parameter	Value
Nominal frequency	50Hz
Capacity	250MVA
Voltage level	16.5kV
Power factor	0.8
Transient reactance X'd	0.23 p.u
Subtransient reactance X"d	0.16 p.u
Current transformer	7600/1 A
Voltage transformer	16500/110V

Protection philosophy calls for slightly different mho blinder settings for a double blinder scheme compared to that of a single blinder scheme, though using the same element names (SEL700G IM). It requires the 78FWD setting to be reduced to establish the outer blinder outside the mho circle. This effort is to ensure that the margin lies below the normal system swing curve, having significant overlap with the loss of field characteristic such that the entire generator impedance is covered:

$$78FWD= 2\times X\_d\hat{}'=2\times 12.69=25.38\ \Omega \quad (3)$$

$$78REV= 1.5\times X\_T=1.5\times 7.12=10.68\ \Omega \quad (4)$$

The outer and inner blinders of this relay are made of 78R1 and 78R2 elements, with the blinders on the left and right being mirror images of each other:

$$78R1= 1/2\ (78FWD+78REV)$$

$$=1/2\ (25.38+10.68)=18.03 \quad (5)$$

$$78R2=1/2\ (Xd'+X\_T)\ \tan(\theta-\alpha/2)$$

$$=1/2\ (12.69+7.12)\ \tan(90-120/2)=5.72\Omega \quad (6)$$

The actual setting may be influenced by stability studies, but it will be limited between these boundaries.

When the perceived impedance passes between the outer and inner blinders, the timer setting is calibrated for the generator's maximum swing rate. The occurrence is considered as a fault rather than a swing and the relay OST function is disabled if the system swing locus moves between the blinders faster than the timer setting 78D. This is comparable to how many concentric characteristic schemes operate for both transmission relays and generators.

The outer and inner blinders must be properly separated to ensure that the relay reliably times the out-of-step slip frequency. Assume the largest out-of-step frequency seen is five slip cycles per second, which corresponds to 30 degrees each cycle (50 Hz). Set the blinders to 70° apart. This distance translates to a 2.3-cycle positive-sequence impedance travel time between the two blinders, which should give appropriate timing accuracy. Set the 78D timer to approximately 0.034 seconds (two cycles), ensuring that 78D will detect swings going at 30 degrees or less every cycle [3].

This relay is programmed to always trip after leaving the mho circle. Before issuing the OOS trip, the 78TD timer adds time after entering the mho circle. When exiting to the left, the maximum angle $\delta = 100.4°$, thus additional delay helps ensure that the trip occurs only when the breaker opening is within the circuit breaker rating ($\delta \leq 90°$). In this scenario, with the same mho circle, add some time after the mho exit based on the generator's lowest projected swing rate against the system:

$$78TD=(\delta-90°)/(\text{minimum swing rate}) \quad (7)$$

$$=((100.4°-90°)/(360°/sec) =0.02889 \text{ second}$$

=1.73 cycles (round of to the nearest 87TD half cycle=2.0)

The minimal amount of time that an OOS trip is held in after it asserts, is often set to be greater than the rated interrupting time of the breaker but less than the breaker failure time by some margin. One can set 78TDURD=3.0 cycles

The OOS characteristic is supervised by this positive sequence current element. It should be configured based on a minimum generation system under stressed conditions (including contingency outages), similar to a fault detector for the farthest-reaching phase distance element in a line protection scheme. It usually doesn't hurt to leave this value at 50ABC = 0.25 amp.

Since no additional supervision will be used for the protection philosophy under study, the OOSTC can be left at a value of 1 which is the default setting of the manufacturer.

TABLE II. SEL700G DOUBLE BLINDER OOS SETTINGS

Relay element	Manufacture typical value	Relay setting
78REV	1.5-2 times X_T	25.38 Ω-sec
78FWD	2-3 times Xd'	10.68 Ω-sec
78R1	1⁄2 (78REV+78FWD)	18.03 Ω-sec
78R2	≤1⁄2 (Xd'+ X_T) tan(θ-α/2) where θ = 90° and α ≈ 120°	5.72 Ω-sec
78D	OOS delay	0.034 sec
78TD	Trip delay timer after Mho Circle exit	0.028 sec
78TDURD	Minimum trip duration timer	3.0 cycles
50ABC	Positive sequence current supervision	0.25 amp
OOSTC	Out-of-step torque control	1

B. Back-up protection (SEL-421)

This section offers step-by-step settings calculations for the SEL-421 relay optimally placed on the Palmiet-Pinotage transmission line to provide back-up protection to the generator OOS functionality for the Palmiet generating units. The SEL-421 features both an out-of-step tripping OST and an out-of-step blocking scheme. Because the operation times of Zones 1 and 2 are often shorter than the times when the impedance of a power swing is present in these protection zones, the OSB logic typically supervises these two zones.

For instance, OSB logic should oversee instantaneous Zone 1 and communications-aided Zone 2 if the period of a swing is 1.5 seconds. Thus, OSB logic will block the phase distance protection during a swing measured within the operating characteristic of the phase impedance elements. It is not required to block all zones in practice, for this study application only Zone 1 and Zone 2 are of interest. Table III lists the system parameters of the subject line.

TABLE III. TRANSMISSION LINE PARAMETERS

Parameter	System Value
Palmiet_Pinotage Line impedance (Z1)	8.032∠83.54° Ω
Zone 2 settings (Z2MP)	9.68∠83.54° Ω
Source Impedance (ZR)	3.22∠90° Ω
Receiving end impedance (ZR)	3.76∠89.5°Ω
Current Transformer	600/1 A
Voltage Transformer	400000/110 V
Nominal Frequency	50Hz
Palmiet_Pinotage Line Length	29.6km

The outermost characteristic in this study is Zone 2, therefore a safety margin of 20% is added for this application purpose [4].

SEL advises assuming that Z1ANG is 90 degrees while setting Zone 6. This enables the user to configure the zone's resistive reach along the x-axis. When the zone setting is applied, the relay will internally modify the setting based on the line angle Z1ANG which then yields the following equation.

R_1R6=1.2·Z2MP/2 =1.2 ×9.64/2=5.78 Ω (8)

Z2MP depicts the zone 2 phase element reach of the mho characteristic.

The maximum load current, I_(L(max), is 0.947A (measured at the secondary of the CT); a power flow study is commonly used to determine this value. When using this information, equation 9 can be used to determine the lowest load impedance (Z_(L(min))) that the relay should measure. The corresponding line-to-neutral voltage when the maximum load is present at the sending generator side is V_LN = 63.5. V secondary.

Z_(L(min)=V_LN/I_(L(max) (9)
= (63.5 V)/(0.947 A)
= 67Ω

Assuming that the maximum load angle is 45° the blinder setting R_1R_7 is given in equation 10

R_1R7=0.9×Z_(L(min))·cos A (10)
=0.9× 67Ω×cos [45°+(90°- 〖Z1〗 _ANG)]
=0.9× 67Ω×cos [45°+(90°-83.54°)]
=37.57Ω

The inner reactance lines X1T6 in Zone 6 should entirely include the outermost zone of phase distance protection that should be prevented from tripping during a power swing. Zones 6 and 7 reactance lines are calculated using equations (11) and (12) respectively.

X_1T6=1.2×Z2MP (11)
=1.2×9.6389=11.56Ω

X_1T7=X_1T6+(R_1R7-R_1R6) (12)
=11.56×(37.57-5.78)=43.35Ω

For OOS blocking delay δ_6 and δ_7 are calculated using the following equations:

$$\delta_6 = 2 \cdot \tan^{-1}\left[\frac{\frac{|Z_T|}{2}}{R_{1R6}}\right] \quad (13)$$
$$= 2 \cdot \tan^{-1}\left[\frac{10.18\angle 83.8°}{5.78}\right]$$
$$= 119.7°$$

$$\delta_7 = 2 \cdot \tan^{-1}\left[\frac{\frac{|Z_T|}{2}}{R_{1R7}}\right] \quad (14)$$
$$= 2 \cdot \tan^{-1}\left[\frac{10.18\angle 83.8°}{37.57}\right]$$
$$= 66.37°$$

5Hz is a typical stable swing frequency used by this vendor, the value can then be used to acquire OSBD setting:

$$OSBD = \frac{(\delta_6 - \delta_7)50Hz}{\frac{360°}{cycle} \times 5Hz} \quad (15)$$
$$= \frac{(119.7° - 66.37°)50Hz}{\frac{360°}{cycle} \times 5Hz}$$
$$= 1.875\ cycles$$

In Table IV the settings configuration suitable for the back-up relay are outlined.

TABLE IV. SEL-421 OOS PROTECTION SETTINGS

Setting	Description	Secondary value entry
R_1R6	Zone-6 Resistance	5.78Ω
R_1R7	Zone-7 Resistance	37.57Ω
X_1T6	Zone-6 Reactance	11.56Ω
X_1T7	Zone-7 Reactance	43.35Ω
OSTD	OOS trip delay	1 cycle
50ABC	Positive current supervision	1A
OSB (1,2,3)	Block Zone	All zones
OSBD	OOS block time delay	1.75 cycles
OOS	Impedance crossing	1

OOS protection is still a very prolific study subject; while the underlying principle remains the same, an incredible number of scholarly articles address the issue of OOS detection and coordination. The most popular detection approach is impedance-based, and it is followed by the most recent methods studied in the literature. Many protection features, such as power swing blocking and out-of-step or pole-slip tripping functions, are built into contemporary distance relays. To distinguish faults from power swings and prevent distance or other relay elements from working during stable or unstable power swings, the power-swing blocking function's primary duty is to distinguish faults from power swings. The majority of power-swing blocking components rely on conventional techniques that track the positive sequence impedance rate. In many situations, especially those where quick swings are likely, it may be challenging to determine the necessary values for the power-swing blocking devices [5].

Out-of-step protection settings are calculated by examining the probable range of apparent impedance trajectories in the R-X impedance plane, as well as the related swing rate. Out-of-step protection can be configured using graphical approaches or by conducting transient stability [8]. While graphical approaches are convenient and straightforward, transient stability studies can be a useful tool for establishing settings or validating the accuracy of settings acquired using a graphical method. The dynamic models of power system elements, specifically rotating machines, and associated control systems, such as the AVR, turbine governor, and Power System Stabilizer (PSS), are studied in transient stability studies.

IV. OUT-OF-STEP PROTECTION SIMULATION RESULTS

A. RMS/EMT Simulations

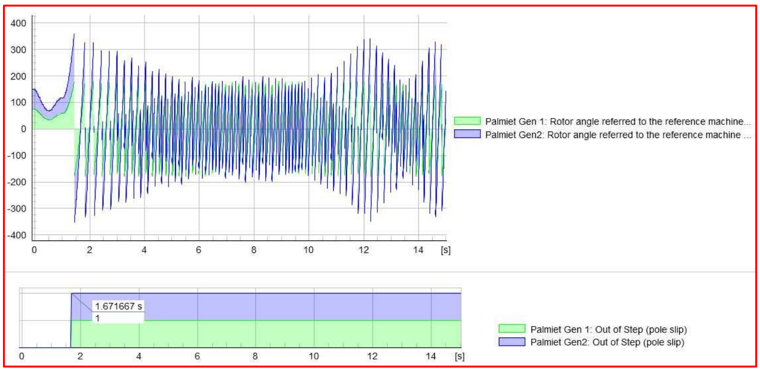
The dynamic behavior of both small and big power systems can be examined using the RMS/EMT simulation features offered by DIgSILENT PowerFactory. The fundamental framework enables the modeling of a wide range of complex systems while accounting for electrical, mechanical, and control aspects, including massive transmission grids, renewable energy facilities, and industrial networks. The main objective of the case studies is to analyse the out-of-step detection based on the angle $firel$ (rotor angle of the synchronous machine concerning rotor angle of the local reference). When the rotor angle $firel$ reaches the detection angle, out of step is detected, whereby the detection angle is set by the user and for this dissertation a value 360° is selected is the relay settings $\alpha = 120°$ which is the separator angle between the generator and the system.

1) Case study - Power swing due to power transfer capability limit

This case study examines and evaluates the performance of the OOS protection scheme and how the entire network behaves when a serious contingency arises in the system. The disturbance used is a 3-bolted short circuit in at Palmiet 400kV busbar to detect a pole slipping situation of the Palmiet generators carrying over their loading capability limit. In a steady state operation, both generators were loading 72.1% and supplying 158.4MW and 86.0Mvar to the system through the Palmiet busbar with a rotor angle of 107.2° Immediately after the simulation at t=1s generators 1 and 2 supplied 37.9MW, 1193.1Mvar with a loading of 477.5% and -4.2MW, 522Mvar with a loading of 209.0% respectively to the station transformers and storage load. From these parameter results reading it is already suspicious that the machines are not in synchronism with the system and each other, however, plots of the simulation results are to follow in the diagrams with Fig 6 showing how the generators detected pole slipping.

Fig 3. Palmiet generators pole slipping detected by DigSilent PowerFactory® simulation.

At $t = 1.672s$ the parallel generators lost synchronism with the system. The machine's rotor angle was gradually increased over the course of the simulation window of 15 s to reach 180°, which prevents the parallel generators from staying in synchronism. Fig 4. illustrates the effect of this contingency on Palmiet Gen 1 speed and rotor angle.



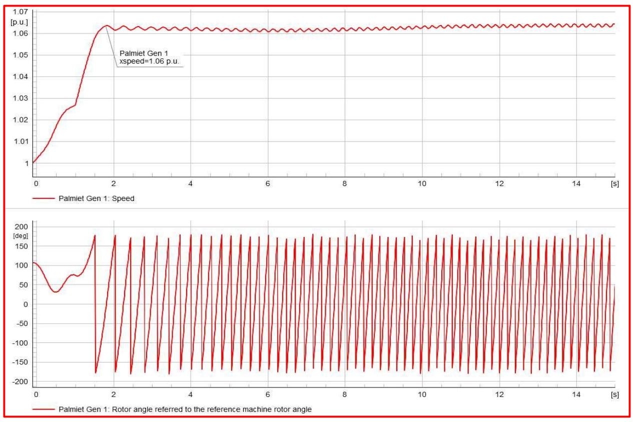


Fig 4. Rotor angle Gen behavior is influenced by accelerating Gen speed.

From this analysis it can be observed that before the contingency we have an internal rotor angle in the synchronous machine, now that a fault is produced at the Palmiet_400kV busbar there is no active power supplied by the 2 parallel generators going to the other parts of the system as there's zero voltage present. As a consequent, there is no electrical power in the machines their rotors are purely driven by mechanical power which in turn this mechanical power is used to accelerate the speed of the generators. As the rotor increases the speed, PowerFactory® creates a plot where a rotor angle is defined from 180° to -180° although it is also oscillating in an accelerated direction. These software limitations create a saw teeth-like graph as seen above

The next simulation event investigates the generator response when OOS trip logic is activated in the protection relay. Asuccessful trip signal the relay sends an output logic to the generator to open its relative breaker at approximately 2s However, the relay binary contact takes about 1s to clear as show in Fig 5..

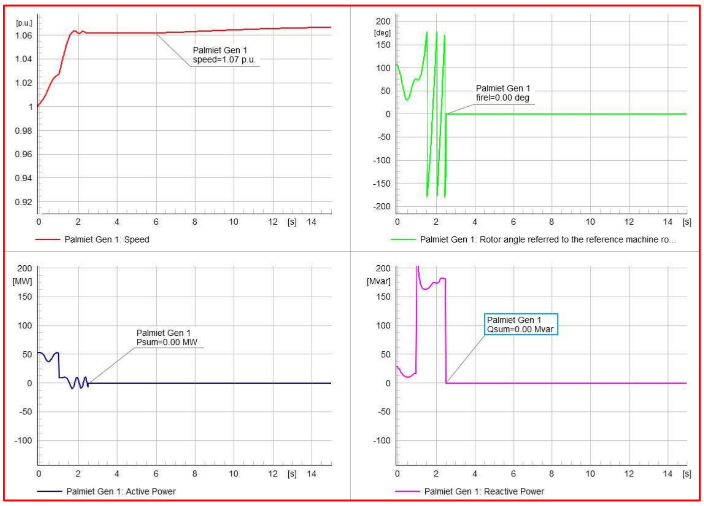
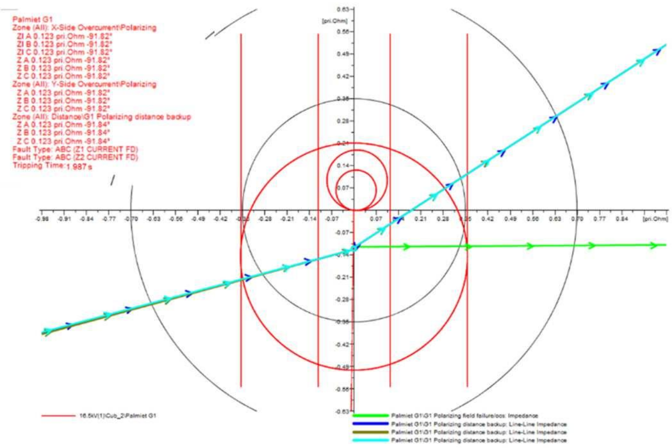
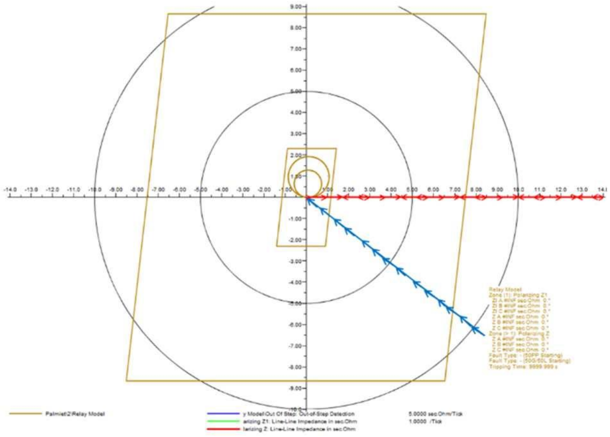


Fig 5. Generator parameters on Gen 1 with OOS protection active and fault cleared.

Due to the rotor's high kinetic energy, it will eventually decelerate as it oscillates in an attempt to reach balance. The non-smooth curve results are due to the system's inertia requiring damping as it is not a traditional two-synchronous generator machine system. When the rotor angle falls to zero, the machine's output power also decreases as the generator breaker opens and stays open until the busbar issue is fixed. .



(a) R-X plot of the SEL-700G clearing OOS.



(b) SEL-421 detecting OOS with SEL700G in-service.

Fig 6. Protection schemes operating for OOS disturbance

Although the SEL-421 relay is slower than the SEL-700G relay and is thus used as a backup protection, it is still capable of detecting OOS conditions during this occurrence. As a result, it won't trip until the primary generator protection is compromised.

V. Discussion of Results

The efficiency of protection devices in managing Out-of-Step (OOS) and Power Swing Blocking (PSB) conditions within a power system. The protection devices, when optimally placed in the system, operate efficiently under OOS and PSB conditions. It is highlighted that the results may not be universally applicable to all generating units in the system due to dynamic loads. This acknowledgment of system-specific dynamics is crucial, and it emphasizes the need to consider the unique characteristics of each unit within the larger power system. The importance of the critical clearing angle/time in mitigating OOS conditions and preventing wear on generators. This is a key finding, suggesting that understanding and optimizing these critical parameters can contribute significantly to the stability and reliability of the system. The simulation results show that the generator speed quickly accelerates to regain stability after a pole slip. This is an essential observation, showcasing the ability of the system to recover swiftly from potential instabilities. The limitation of the time stamp in the simulation to 15 seconds is noted as potentially impacting the clarity of the results, particularly regarding the speed's return to operating equilibrium. Consider providing additional information on how the time limitation might influence the interpretation of the results. The system under test is not a classical two-machine system is noted. It is essential to clarify how the system's complexity and non-classical nature influence the speed's return to equilibrium and the overall behavior observed in the simulation. An adaptive Out-of-Step (OOS) protection scheme refers to a protection system that can dynamically adjust its settings or operation based on real-time conditions, utilize advanced algorithms or intelligence, and continuously monitor and analyze the power system's behavior. This adaptability enhances the reliability and effectiveness of the protection system in preventing out-of-step conditions.

VI. Conclusion

The paper introduces the concept of adaptive OOS protection, emphasizing its role in preserving power system rotor angle stability. This is a critical aspect of power system operation, especially with the increasing integration of renewable energy sources. The use of the DIgSILENT software package for simulating stable and unstable power swings in a modified Eskom west grid transmission system adds credibility to the research. Consider providing some key details on the modifications made to the Eskom grid for simulation purposes. The paper suggests that the adaptive OOS protection for generators offers better reliability due to its speed and selectivity in tripping out breakers. This observation positions the proposed protection scheme as a potential improvement over the existing line impedance relays. The suggestion that utilities could consider adopting the proposed generator OOS tripping scheme instead of line impedance relays is noteworthy. Consider elaborating on the advantages and potential challenges associated with the adoption of this new scheme by industry practitioners. The objectives of system operators emphasize the importance of preserving the machine from damage after an OOS occurrence and minimizing disruptions. The SEL700G offering a robust solution adds specificity to the proposed protection method. The importance of deploying fast-tripping relays in power system protection highlights the criticality of timing in preventing equipment damage and unnecessary outages. The OOS generator protection ensures continuity of supply by isolating only the generator-associated breakers, leaving standby generators in service. This is a crucial aspect in ensuring uninterrupted power supply.

Acknowledgment

The authors acknowledge Cape Peninsula University of Technology to offer the facilities to carry out this research work at the CSAEMS. This research was funded in part by the NRF Thuthuka Grant, Number 138177, SANEDI JET RFQ062, Eskom Tertiary Education Support Programme (TESP) and Council for Scientific Industrial Research institute (CSIR) funding towards the carrying out of the research work.

References

[1] D. Hou and D. Tziouvaras, "Out-Of-Step Protection Enhancements," in *Developments In Power System Protection, Eighth IEEE International Conference.*, USA, 2004.

[2] A. Sallam and O. Malik, "Power System Stability: Modelling, Analysis and Control," *Power system stability overview.,* pp. 1-10, 2015.

[3] . A. Sauhats, A. Utans, D. Antonovs and . A. Svalovs, "Angle Control-based Multi-terminal Out-of-step Protection System.," *Energies,* 2017.

[4] M. Acosta, F. Gonzalez-Longatt, C. Topi and M. Andrade, "Microgrid–InteractiveReactive Power Management for Day–Ahead Operation," *Energies,* vol. 14, p. 1275, 2021.

[5] F. Gonzalez-Longatt and J. Rueda Torres, "Advanced Smart Grid Functionalities Based on PowerFactory, Green Energy and Technology," in *Springer International Publishing*, AG, 2018.

[6] J. Thorp, A. Phadke, S. Horowitz and M. Begovic, "Some Applications of Phasor Measurements To Adaptive Protection," in *IEEE Transactions on Power Systems*, 1988.

[7] H. Chamorro, A. Orjuela-Canon, D. Ganger, M. Persson, F. Gonzalez-Longatt, L. Alvarado-Barrios, V. Sood and W. Martinez, "Data Driven Trajectory Prediction of Grid Power Frequency Based on Neural Models," *Electronics,* vol. 10, no. 151, 2021.

[8] H. Chamorro, F. Sevilla, F. Gonzalez-Longatt, K. Rouzbehi, H. Chavez and V. Sood, "Innovative primary frequency control in low-inertia power systems based on wide-area RoCoF sharing," *IET Energy Syst. Integr,* vol. 2, pp. 151-160, 2020.

[9] P. Kundur, J. Paserba, V. Ajjarapu, G. Andersson, A. Bose, C. Taylor and D. e. a. Hill, "Definition and Classification of Power System Stability IEEE/CIGRE Joint Task Force on Stability Terms and Definitions," *IEEE Trans. Power Syst.,* vol. 19, pp. 1387-1401, 2004.

[10] N. Fose, "APPLICATION OF IEC 61850-90-5 STANDARD-BASED PREDICTIVE DYNAMIC STABILITY SYSTEM," MENG Thesis, CPUT, Cape Town, 2023.

[11] S. Krishnamurthy and B. Elanga Baningobera, "IEC61850 standard-based harmonic blocking scheme for power transformers," *Prot Control Mod Power Syst* , vol. 4, no. 10, 2019.