2022 IEEE PES/IAS PowerAfrica

Reliability and Security Analysis of The Southern Africa Power Pool Regional Grid

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2022 IEEE PES/IAS PowerAfrica | 978-1-6654-6639-4/22/$31.00 ©2022 IEEE | DOI: 10.1109/PowerAfrica53997.2022.9905389

***Abstract*—Over the last decade, Southern Africa has experienced power outages. This is due to insufficient electrical power supply systems, as well as load development in areas that were not sufficiently planned for. The Southern African countries can have a reliable, sustainable, and efficient electrical power grid with the use of power interconnections to exchange power. The primary difficulty with the present grid is to generate electricity using the old electrical infrastructure while also serving loads inside national borders. Most Southern Africa interconnections were implemented in 1995, after the formation of the Southern African Power Pool (SAPP). It was discovered that when electricity interconnection grows larger, the network system becomes more complex. Additionally, power connectors may encounter issues with frequency and voltage control. Numerous Southern African countries are unable to fulfill peak demand within their borders due to population ngrowth and aging infrastructure, resulting in electrical shortages. This article discusses the results on how to improve grid reliability by controlling voltages with a static var compensator. The remainder of the study discusses an efficient technique for optimizing the current SAPP power network through the use of High Voltage Direct Current Line Commutated Converter (HVDC-LCC) links and as a component of the Flexible AC Transmission System (FACTS).**

Keywords*—Grid reliability, smart grid utility, HVDC links, power interconnection, FACTS.

I. Introduction

An interconnection is formed when two or more power utilities with transmission lines physically link. This optimizes the use of existing electrical resources and the sustainability of the environment [1]. HVDC transmission systems are cost-effective for long-distance power transmission and connectivity of numerous networks operating at varying voltages and frequencies [2]. [3, 4] detail a few of the technological advantages of linked systems. Most crucially, power utilities pool their operational reserves to provide mutual assistance in the event of a generator trip or scheduled outage. Voltage support is provided through reactive power support resources shared across electricity-linked utilities [5]. The more coupled the networks are, the more resilient the disturbance is [1]. The reliability of a power system is a measure of the grid's or network's ability to withstand network shocks, which are unexpected disruptions such as a generator trip or a rapid load increase, as well as other unpredictable occurrences in an electric network. Security and system dependability must constantly be adhered to. The following properties of a dependable grid network are present [6, 7]:

- The grid that can withstand the loss of one transmission line.
- Acceptable voltage in every busbar of the system.
- Components such as transformers, generators, and transmission lines must not be overloaded.
- Its generating capacity must be greater than the load demands all the time
- Ability to preserve stability when a short circuit occurs.
- It must be able to withstand the loss of generators.

Frequent blackouts or power outages are obvious symptoms of an unstable electric grid [8]. Although linked electricity grids are recognized to be extremely safe and dependable, their complexity means that unanticipated events such as poor connections, human mistakes, malfunctions, and a breakdown in the protective plan might occur, resulting in a cascade [1]. The proposed power interconnection is a smart grid network capable of intelligently integrating all customer actions, from generators to consumers, to supply sustainable, secure, efficient, and cost-effective electricity [9]. The SAPP grid's primary motivations and benefits are summarized in [9, 10]. An intelligent SAPP grid must include sophisticated energy management tools, condition monitoring equipment such as phase measurement units (PMUs), protection or through state estimation tools, ICT capabilities, and innovative technologies such as self-healing, and efficiency gains [11]. supervisory control and data acquisition, and energy management system (SCADA/EMS) for system monitoring. Other techniques to control and protection [12, 13].

II. SAPP Power Grid

SAPP consists of ten member countries: South Africa, which generates approximately 93 percent of Africa's coal [14, 15]. Angola, one of the Africa's largest oil producer [16], Malawi, has less than 10% electricity access [17]. Namibia and Swaziland import electricity from South Africa and Mozambique; Zambia generates 95% of its electricity from hydro; and Zimbabwe which relies heavily on coal. Botswana imports from South Africa but is becoming self-sufficient in electricity. Lesotho's 80MW installed capacity meets its 155MW demand [18]. Mozambique has a hydropower potential of 19GW [19]. Malawi is not currently connected to any of the SAPP nations.

The SAPP region's present and prospective electricity interconnections are depicted in Fig.1. The dark green counties are those that are operational member counties and are connected. The light green countries are those that are not operational - those that are not electrically interconnected [14]. All of these power linkages were created with the same objective in mind: to optimize available resources and energy exchange.

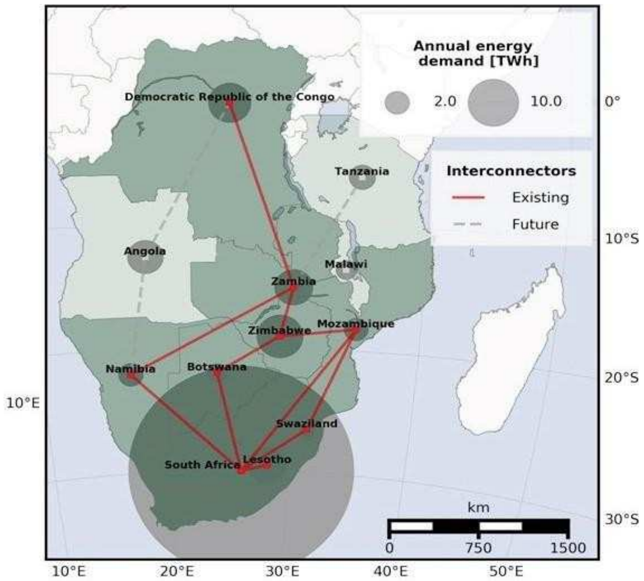

Fig. 1. SAPP existing and future power interconnection [14].

Table I. compares each country's installed capacity to its peak demand in the SAPP region. Countries such as Swaziland and Lesotho cannot meet the load demand within their country, while other countries such as South Africa and Angola have reserve capacity. Through interconnections, the weaker countries can increase electricity access.

TABLE I. INSTALLED CAPACITY VS THE DEMAND OF THE COUNTRY

Name	Installed capacity (MW)	Peak demand (MW)
South Africa	52028	46678
Angola	6143	3378.65
Malawi	362	470
Zambia	2493.5	2300
Namibia	508	600
Botswana	890	702
Mozambique	3001	1650.55
Lesotho	80	155
Swaziland	64	223
Zimbabwe	2037.25	2200
SAPP	67606.75	58357.2

TABLE II. TRANSMISSION LINES LIMIT CONSTRAINTS

Line	Thermal limit (MW)	Stability transfer (MW)
Matimba-phokoje	650	190
Insukamini -Phokoje	700	220
Insukumini - marvel	84	81
Insukumini - Hwange	880	814

This research analyzes the interconnections between three SAPP member countries as shown in Table II: South Africa, Botswana, and Zimbabwe. South Africa generates energy at the Matimba coal-fired power plant; Botswana generates electricity at the Phokoje thermal power station, and Zimbabwe generates electricity at the Marvel and Hwange power stations.

III. STEADY STATE STABILITY

The terminology "system reliability" relates to the network's capacity to supply sufficient, reliable, and steady electricity to a particular distribution [20]. "Steady-state security" refers to power systems' resistance to disruptions and time [7]. Numerous approaches are employed to ensure and improve the system's stability, including monitoring, information management, automation, the introduction of smart grids, and the deployment of novel technologies mentioned before. Thus, all busbar voltages must be maintained within a 5% tolerance oftheir nominal value. In the event of an emergency, no equipment should be loaded over 105 percent. However, a 15% overvoltage for a brief period of 5 seconds is okay, as isa 20% overvoltage for 1 second.

A. High Voltage Direct Current Line Commutated Converters

The generation, transmission, and distribution networks are critical in power systems [21]. VSC HVDC schemes are better for long-distance and multi-terminal grids. LCC HVDC systems may be used for large networks over long distances to control voltage using reactive power [22]. HVDC technology is the most appropriate in the super grid for effective operation control, eliminating intermittency difficulties in the generation, and therefore enhancing the built-in redundancy incapacity [23, 24].

B. FACTS Characteristics

The power interconnection network model connecting these three counties is complicated, posing difficulties in fulfilling rising electricity demand while maintaining fair electricity costs for customers. The transmission network extension reduces system stability and increases the probability of blackouts and cascade failures. FACTS devices are proposed for use in a prospective Smart African Super Grid to improve the transmission system's integrity while increasing the quality of power transfer capabilities. FACTS devices improve power transfer capacity by 20-30%, manage power flow, improve power system stability, assure flexible system operation, decrease flickering, and promote effective use of existing grid infrastructure [25, 26]. The Static Var system, which is part of the FACTS system, was adopted in this investigation to control the voltage of the system [27].

C. Smart Grid Technologies

A smart grid is an electricity network that intelligently integrates all customers to provide sustainable, secure, efficient, and cost-effective power [9]. For optimal realization, advancements in smart device technology are required. This includes smart meters that will assess the energy use and power quality of each piece of electrical equipment that is connected to it. Smart technologies include artificial intelligence control devices that can forecast problems in advance and monitor network power efficiency. Power electronics and real-time transmission power flow control devices are also incorporated, which may limit and correct waveform deformities induced by either the generator or the load [12].

IV. Model Development

The model was constructed on the DIgSILENT PowerFactory tool utilizing the acquired network data and the rules used when designing the network system.

Fig. 2. depicts three HVAC power interconnections ofthree SAPP utilities among three SAPP regions to supply power to the Phokoje utility in Botswana. Matimba has six generating units, each of which produces 665MW, Phokoje has four generating units, which each produce 150MW, and Hwange has six generating units, four of which produce 120MW and the other two which produce 120MW [16, 28].

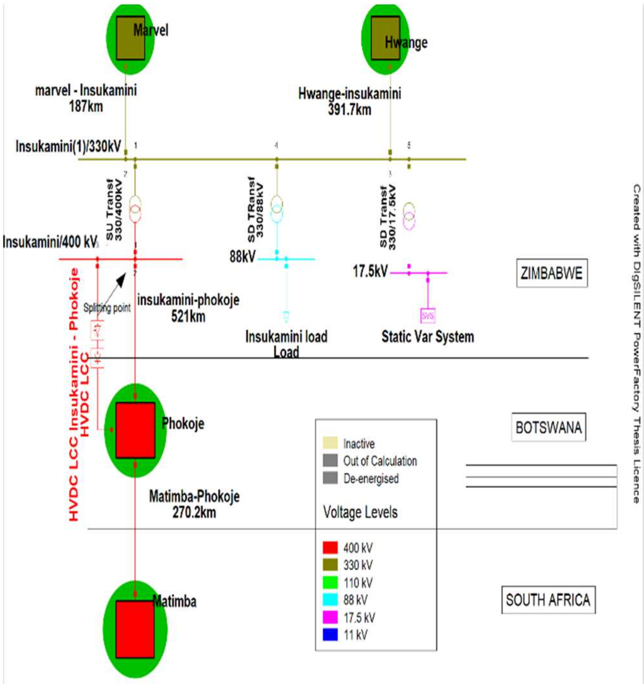

Fig. 2. The 400Kv South Africa – Botswana – Zimbabwe Interconnection with the splitting point at Insukamini in Zimbabwe.

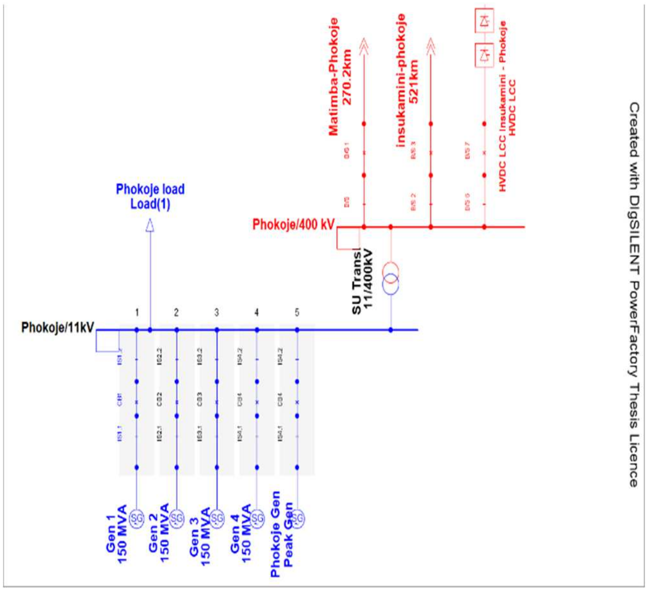

Fig. 3. Phokoje utility with two HVAC Interconnections.

Fig . 3. shows the Phokoje utility model in Botswana, with two HVAC lines originating from both Insukamini and Matimba. There are limitations used to maintain network reliability, such as the voltage must be within the nominal range of 95 percent and 105 percent, overloading of components such as generators must be avoided, and acceptable thermal loading of components must be within the range of (80 % - 100 %).

This analysis was carried out using the Newton Raphson algorithm to analyze load flow in a system.

$$S_i = V_i \sum_{j=1}^{n} Y_{ij}^{*} V_j^{*} = \sum_{j=1}^{n} |V_i||Y_{ij}| \angle \left(\delta_i - \delta_j - \theta_{ij}\right) \quad (1)$$

Whereby

$$Y_{ij} = |Y_{ij}| \angle \theta_{ij}, V_i = |V_i| \angle \delta_i and V_j = |V_j| \angle \delta_j \quad (2)$$

The real P_i and reactive Q_i powers for each bus in a power network are obtained by [29].

$$P_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \cos\left(\delta_i - \delta_j - \theta_{ij}\right) \quad (3)$$

$$Q = -\sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \sin(\delta_i - \delta_j - \theta_{ij}) \quad (4)$$

Thermal loading is calculated using the ratio of load current to rate current.

$$thermal.loading = \frac{Iload}{Irated} X100\% \quad (5)$$

Whereby the load current per phase:

$$I_l = \frac{S_{l3\phi}^{*}}{3V_l^{*}} \quad (6)$$

The current flowing in HVDC LCC Link is given by:

$$I_{dc} = \frac{V_{dc}\cos\alpha - V_{dc}\cos\delta}{R_l + R_r + R_i} \quad (7)$$

Such that

$$V_{dc} = \frac{3\sqrt{2}}{\pi} V_{ac} \quad (8)$$

And for short circuit voltage the impedance is:

$$Z_{new}[p.u] = Z_{old}[p.u].\left(\frac{V_{old.base}}{V_{new.base}}\right)^2 \left(\frac{S_{new.base}}{S_{old.base}}\right) \quad (9)$$

V. Modeling and Simulation Results

To run the simulations, a network of three interconnections between SAPP nations was established using the DIgSILENT PowerFactory Software tool and the previously obtained data, as shown in Fig. 4. The model is simulated to analyze the performance of voltage across transmission lines, and the generators are loaded within 80% and 100% to create their maximum active power.

Fig. 4. shows the model for the Phokoje power substation with four generating units to produce power. The generating units are within the range of (80%-100%) of their installed capacity.

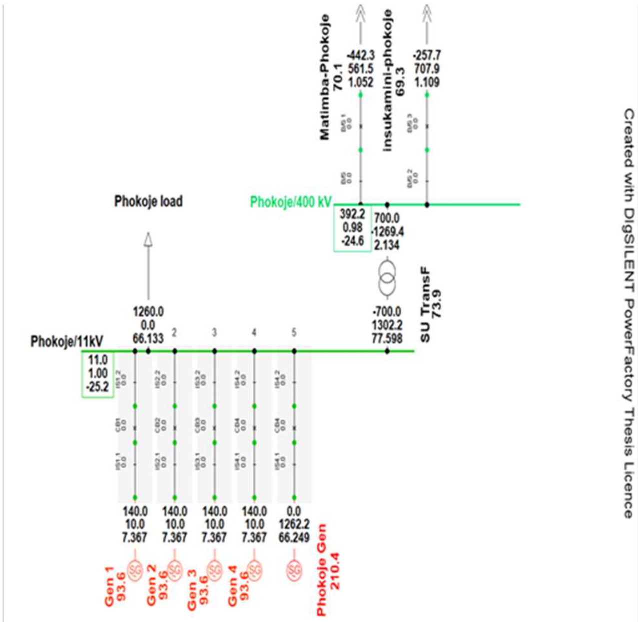

Fig. 4. Phokoje utility model with two HVAC Interconnections.

Phokoje station receives 700MW from Insukamini and Matimba. 442.3MW is from Matimba and 257.3MW is from Insukamini. All four operational substations, Marvel, Hwange, Phokoje, and Matimba, were originally drawn separately and then combined to make one power interconnection.

The complete grid in Fig.6. was simulated on DIgSILENT PowerFactory software using Newton's Raphson technique onequation (1) – (4). The HVAC lines leading to the Phokoje substation are depicted. Insukamini exports 700 MW, however owing to losses, Phokoje receives only 257.7MW, while Matimba exports 648.7MW. Phokoje receives 442.3MW due to losses.

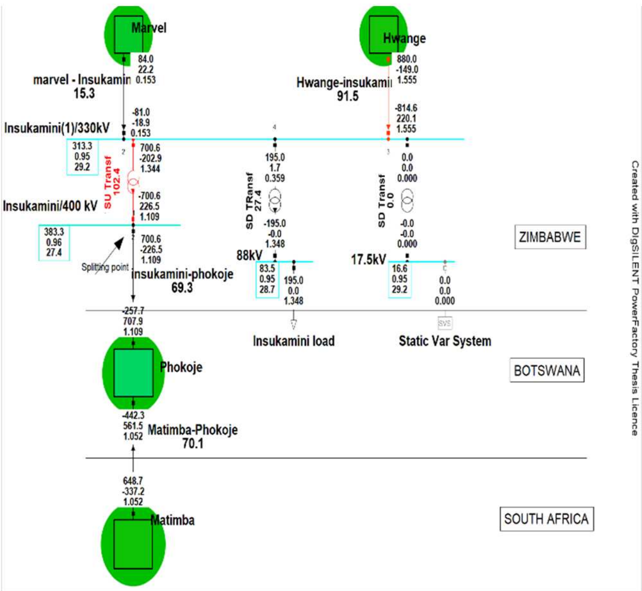

Fig. 5. The 400kV network model of three SAPP countries.

The static Var system is turned off in this simulation, and the Insukamini busbar voltages are 0.95 p. u. and 0.96, illustrating one of the problems of a reliable grid.

As illustrated in Fig. 6, the Static Var compensator is a FACTS device that is mostly used for voltage management by controlling a certain amount of reactive power. Voltages in Insukamini are presently 1.0 p.u. and 0.99 p.u. In Fig. 6, active electricity exported from Insukamini to Phokoje is increased to 291.8MW, up from 257.7MW in Fig. 5.

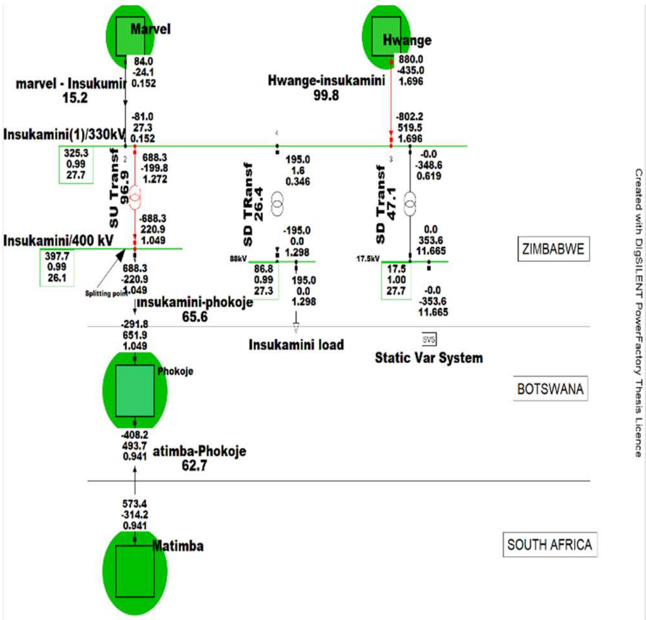

Fig. 6. Grid model with static Var system.

Fig. 7. depicts the power of HVDC, which in this case is LCC, to optimize power using equations (7) and (8), the exported power from Insukamini to Phokoje is now 384.4MW, while when the power set point in LCC-HVDC is 100MW.

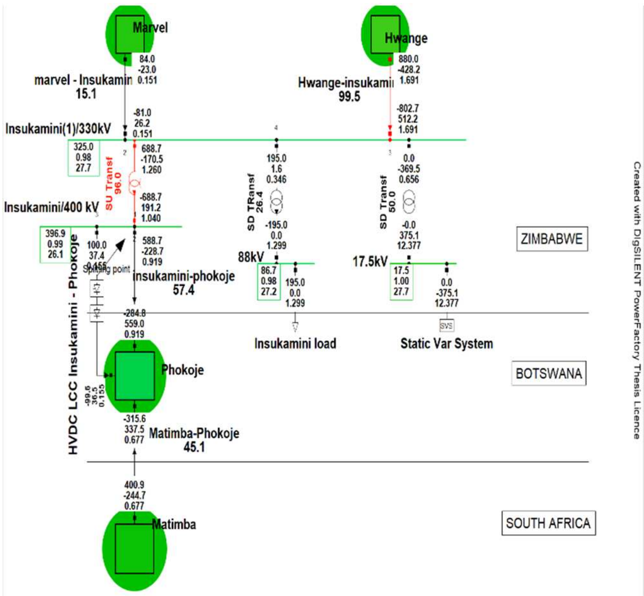

Fig. 7. The 400k V network model with HVDC LCC and Static Var System.

Fig.5. depicts the susceptibility of interconnections between three SAPP nations, where line losses are substantial

and voltages are much lower than 1.0 p.u. In Fig. 6, the voltages are adjusted to approximately 1.0 p.u. using a static Var compensator, making the grid more reliable, and the reactive power regulated.

VI. CONCLUSIONS

Through this investigation throughout this paper, it can be concluded that HVDC and FACTS devices offer a better solution when transmitting bulk power over a long distance, these devices make a grid to be more robust even against unforeseen events. The active power exported from Insukamini to Phokoje is increased. Fig.7. depicts a network model of three SAPP counties with optimal power exported from Insukamini to Phokoje via an HVDC LCC-HVDC system and an SVC. The voltage is controlled and the power is optimized through HVDC LCC and Static Var System.

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