A Load Flow Analysis of the Southern African Power Pool Interconnections using High Voltage AC, High Voltage DC, and Flexible AC Transmission System

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***Abstract*—Globally, the importance of power interconnections is growing due to the possibility of power exchange, Thus, the effective solution of bulk power transmission over large distances is achievable with High Voltage Alternating Current (HVAC) which has losses along the transmission line. High Voltage Direct Current (HVDC) uses converters to transform AC power into DC, resulting in superior active and reactive power compensation and reduced losses. The Flexible AC Transmission System (FACTS) combines shunt and series convectors for improved voltage control and power stability, and it enables the transmission of large amounts of electricity over long distances with lower losses than a conventional system. This study implements a load flow model between three substations with bulk power coupled by long-distance transmission lines to compare and conclude which technology is best for transferring bulk power over long distances to offer secure and sustainable electricity.**

Keywords—Flexible AC Transmission System (FACTS), High Voltage Alternating Current (HVAC), High Voltage Direct Current (HVDC), Power Exchange, Power interconnection.

I. INTRODUCTION

The majority of countries face numerous issues when it comes to electricity use [1]. The power interconnection offers a significant change that allows the export of electricity to developing countries through transmission linesusing HVAC, HVDC, and FACTS [2]. Thus, in comparison to HVAC, HVDC enables the transportation of large amounts of power over thousands of kilometers (km) with reduced losses than HVAC, as losses rise with length [3]. Population growth increases power demand, which affects voltage stability and unbalanced reactive power [4]. FACTS devices are recognized as the optimal technique for stabilizing the system voltage and optimizing the system's power to improve the power grid's stability. It is characterized as the precise operation of the electric grid to restore equilibrium following an abnormal circumstance suchas a generator trip, low or high voltage, increase in power consumption, or load rejection [5]. Consequently, the overhead transmission lines are considered a critical component of the power system since they transport electricity from generators to load centers [6].

This study uses three Southern African Power Pool (SAPP) substations (SS) to power load centers far from the generating plant. These three utilities exchange electricity on demand. This research is inspired by current and proposed interconnections in the SAPP, such as Zambia and Zimbabwe's power interconnection between Kariba North and Kariba South SS. South Africa, Botswana, and Zimbabwe export power from SA's Matimba and Zimbabwe's Insukamini to Botswana's Phokoje SS [7]. The ZIZABONA power interconnection with four countries – Zimbabwe, Zambia, Botswana, and Namibia – includes a 400kV, 101km line connecting Hwange and Livingstone via Victoria Falls, a 400kV, 231km line connecting Livingstone and Zambezi, and a 400kV, 76km line connecting Victoria Falls and Pandamatenga [8]. Proposed 210km BO-SA Power interconnection between Botswana and South Africa for a 400kV transmission line between Mahikeng, South Africa, and Gaborone, Botswana [9]. Southern Africa has 10 countries: South Africa, Lesotho, Swaziland, Namibia, Botswana, Zimbabwe, Zambia, Malawi, Angola, and Mozambique. Malawi and Angola are not connected to SAPP. Malawi has an installed capacity of 362 MW to meet a demand of 472 MW, and its electricity access is approximately 12%, SAPP has about 67.71GW installed capacity, a population of 180.121 million, and a peak demand of approximately 46678MW, implying that by utilizing power connections in the SAPP region, all countries can have access to electricity [10, 11].

Power-sharing has various possible benefits, including increased influence over public policy, the inclusion of all members involved in decision-making, and increased political order stability [12]. Other advantages of increasing the electricity market among SAPP countries include cost reduction through increased market competition, enhanced electricity supply, cost savings through less generation reserved, and effective resource usage through generational pooling [13].

This article discusses how power exchange can be done in SAPP countries to expand electricity access. This research is based on three SAPP countries: South Africa with Eskom Utility, Swaziland with SEC Utility, and Mozambique with EDM Utility. and within this utility, this study is utilizing Matimba SS, Edwaleni SS, and Cahora Bassa to exchange power to satisfy their growing demand.

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II. IMPLEMENTATION OF SAPP POWER GRID

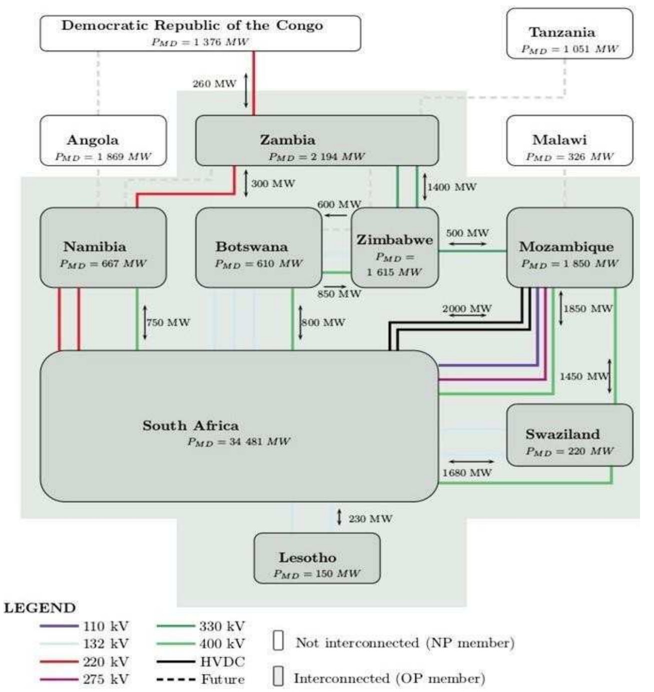

Fig. 1. Example SAPP Existing and planned power interconnections (2016)

Fig.1. illustrates all of the countries connected to the SAPP's member countries [14]. SAPP was formed in 1995 [15]. The purpose of constantly altering the pool was to develop a more efficient regional power distribution system; the distribution of energy sources within the region is the rationale for power exchange [16]. This study is focusing on countries that currently lack access to electricity to meet rising demand. Swaziland is the study's target country, with approximately 12 percent of the population having access to electricity. With the assistance of power exchanges and interconnections, Swaziland will be able to increase electricity access in the country. Table I stipulate the transmission lines distances and the generating unit of each SS

TABLE I. TRANSMISSION LINE LENGTH & THE SS GENERATING UNIT

SS Name	Generating unit (MW)	Transmission line (Km)
Matimba SS	6x665	Matimba – Edwaleni (495)
Edwaleni SS	1x5 & 4x3	Matimba – Cahora Bassa (1439)
Cahora Bassa	5x415	Edwaleni – Cahora Bassa (1210)

III. TRANSMISSION LINE TECHNOLOGY

Due to population growth, Southern Africa needs to meet electrical demand and modernize its power infrastructure to boost electricity generation. Even with existing infrastructure, operating a large interconnected power system is complicated, resulting in power loss, voltage instability, and unreliable operation [17]. Switching from HVAC to HVDC may be cheaper for long-distance electricity transmission. DC lines are more advantageous over 500km because they have no reactance and can transfer more power for the same conductor size [18]. Compared to HVAC, HVDC is most often used to integrate, collect, and transmit large-scale renewable resources to load centers. This grid boosts reliability, flexibility, and redundancy by sharing resources [19, 20]. According to [18]. DC is preferable. Due to their superior qualities, smart super grid development, creative applications, and merging of HVDC and FACTS are occurring [21].

HVDC and FACTS can handle the planning system, which requires changes in how the system is supplied. New electronic power technologies with self-commutated converters can supply weak or passive networks and control reactive and active power separately. FACTS devices and HVDC increase transmission line capacity [21]. Unified power flow controllers (UPFCs) and static compensators (STATCOMs) may solve power system reliability issues. UPFCs are FACTs devices capable of series and shunt compensation to minimize power quality disturbances in a power system [22]. This research used the Static Var system (SVC) as part of the FACTS devices to manage system voltage by managing reactive power [4]. The advantages of HVDC over HVAC are stipulated in [23] And Fig.2. HVDC Line Commutated Converters (LCC) is used in this study to compare with HVAC. HVDC LCC's benefits and characteristics are listed in [24].

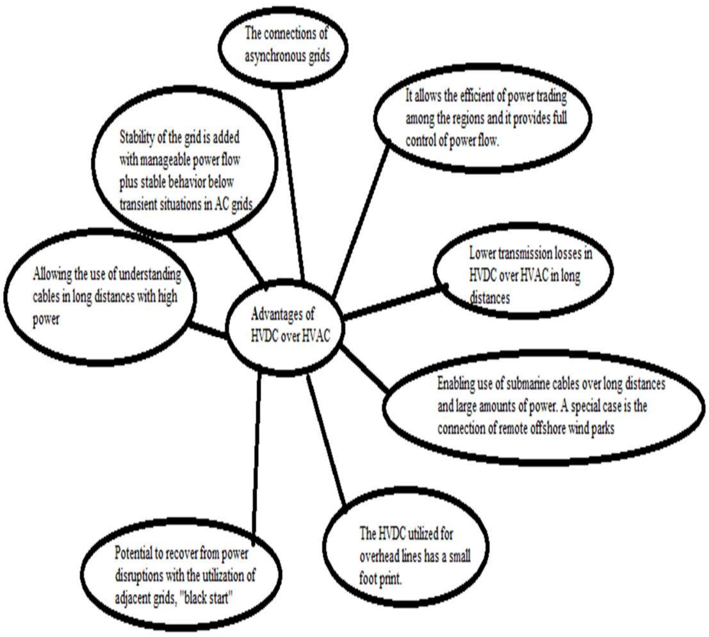

Fig. 2. Advantages of HVDC over HVAC.

IV. SAPP POWER GRID LOAD FLOW MODELS OF THREE POWER UTILITIES

The SAPP power grid is implemented under the supervision of a reliable grid, which is essential for every grid to have strong reliability; the characteristics of a good power grid are mentioned below.

- The grid that can withstand the loss of onetransmission line
- Acceptable voltage in every busbar of the system
- Components such as transformers, generators, and transmission lines must not

beoverloaded.

- Its generating capacity must be greater than theload demand all the time.

Frequent blackouts or power outages are an obvious symptom of an unreliable electric grid [25]. Interconnected power grids are generally safe and reliable, but due to their complexity, inadequate connections, human errors, malfunctions, and protective strategy failure leading to a cascade may occur [7]. Thus the transformers, generators, and line loading must bewithin the limit of (80% - 100%), and all the Busbar Voltages must be kept within the tolerance of ± 5% of their Nominal value

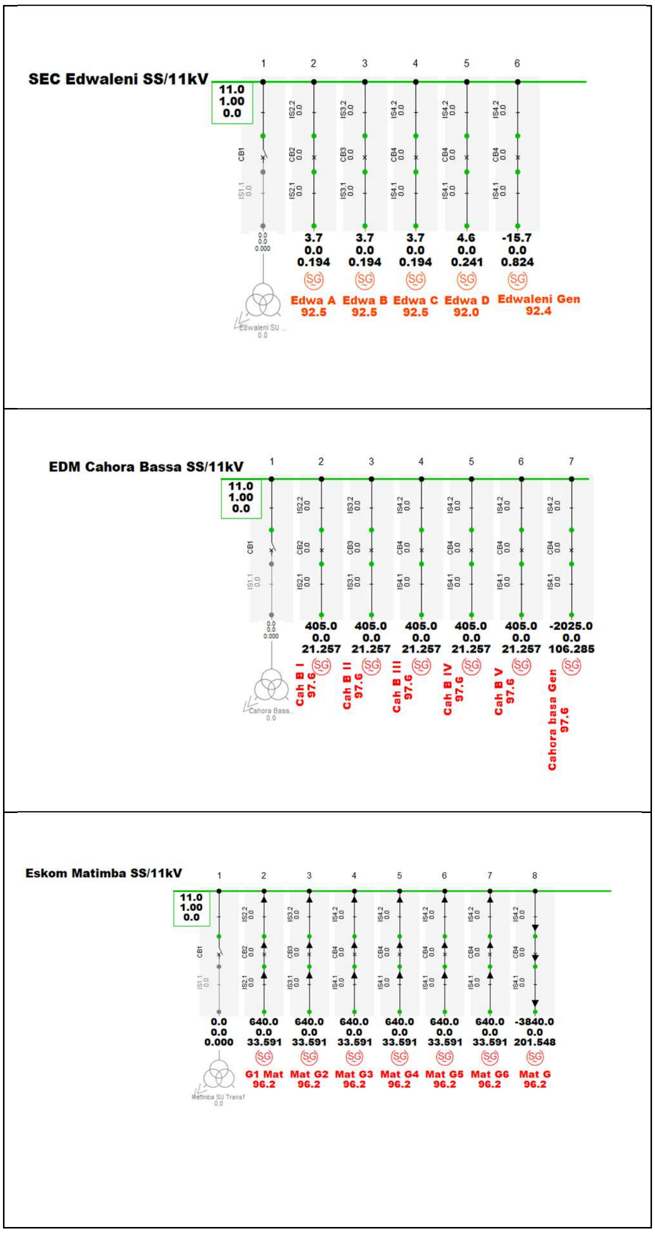

Fig. 3. Edwaleni, Cahora Bassa & Matimba SS.

Each SS was built separately, as shown in Fig.3. The Matimba SS has (6 x 665 MW) installed capacity on their generator and all produce an active power of 3840 MW, Edwaleni SS has (3 x 4MW) and (1 x 5 MW) installed capacity and produces a maximum power of 15.7MW, and Cahora Bassa has (5 x 415MW) installed capacity and produces a maximum power of 2025MW. As previously stated, Swaziland is the most disadvantaged of the three SAPP countries, with a total installed capacity of only 64MW attempting to meet a demand of 223 MW.

The load flow model in Fig.4. is built with three power utilities from various SAPP countries. Matimba from Eskom, Edwaleni from SEC, and Cahora Bassa from EDM, with the primary goal of increasing Edwaleni SS's access to electricity. The spacing between the substation and their load center is fixed at 100km. Fig.3. shows how these SS are interconnected

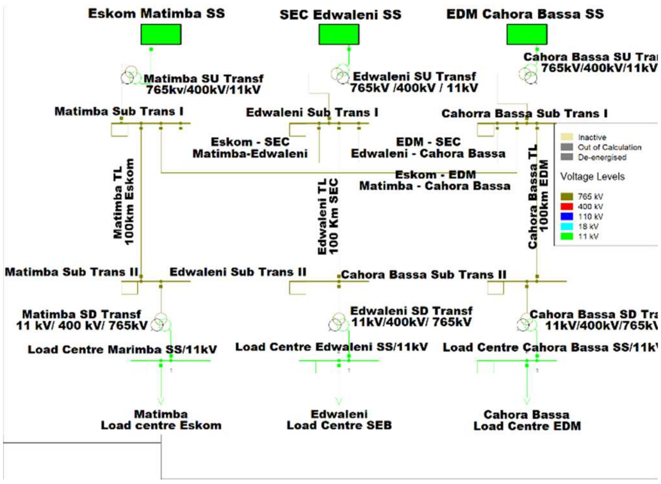

Fig. 4. SAPP Power Grid HVAC connecting three SAPP countries

The load flow study is carried out by adjusting the loads on the electric network and analyzing the entire system behavior such as line overload, power loss, and voltage stability, as shown in Fig.5. When operating alone, Edwaleni SS can only produce 15.7MW. With the power interconnection shown in Fig.5. the three load centers are fed with 1000MW each, with Cahora Bassa and Matimba SS exporting 623 MW and 387.8 MW, respectively, though some power is lost along the transmission line. As previously stated, the electricity grid is still running within the restricted limit.

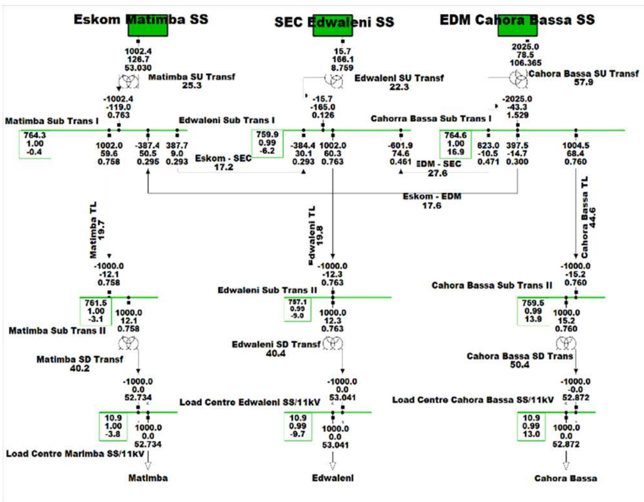

Fig. 5. SAPP Power Grid with three 1000MW SS interconnected.

As illustrated in Fig.6, the load flow model is run again with an increase in their load cent In Fig. 6, the load flow model is run again with an 1800MW load center. The Edwaleni Network has voltage instability..

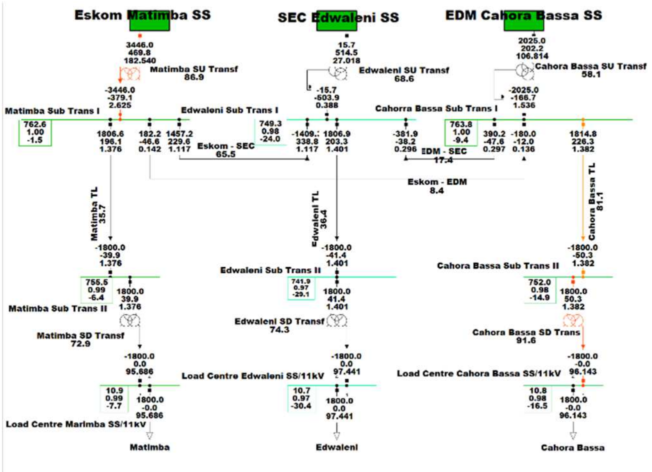

Fig. 6. Three interconnected SS with 1800MW load each.

In Fig.7, Matimba SS and Edwaleni SS were modeled with a 2000MW load. Edwaleni SS voltage instability increases with load demand. Edwaleni SS imports 471.9MW from Matimba and 1590MW.

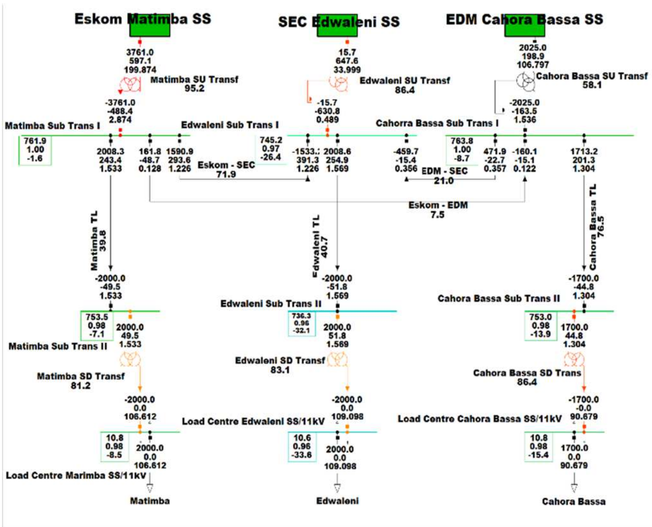

Fig. 7. Three SAPP SS with different load demands.

This power interconnection is performed over long distances, resulting in power loss across the transmission line. The load flow using the HVDC LCC link is carried out to minimize losses in Fig.8. as compared to Fig.7., whereby Eskom – EDM TL transports 161,8MW and can transmit 205,4MW with the addition of HVDC LCC.

The load flow is implemented again in Fig.9 by employing HVDC LCC in (EDM-SEC) with 1210km TL length and power set point of 300MW in HVDC line to support and enhance HVAC line of EDM – SEC. The losses are minimized, and the power is optimized with the help of the HVDC LCC link, but the voltage instability is still affecting the system, as seen in Fig. 8 and 9.

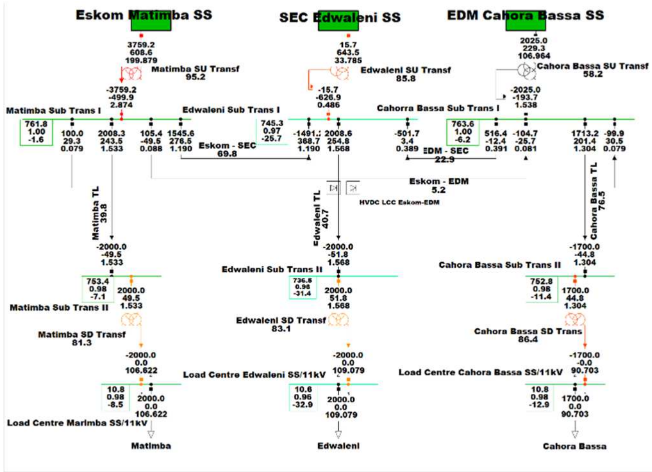

Fig. 8. Three SAPP SS utilities with HVDC LCC (Eskom-EDM)

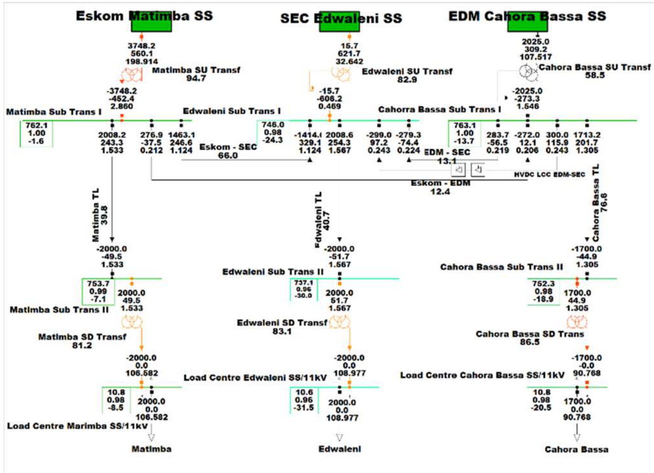

Fig. 9. Three SAPP SS with HVDC LCC in EDM-SEC.

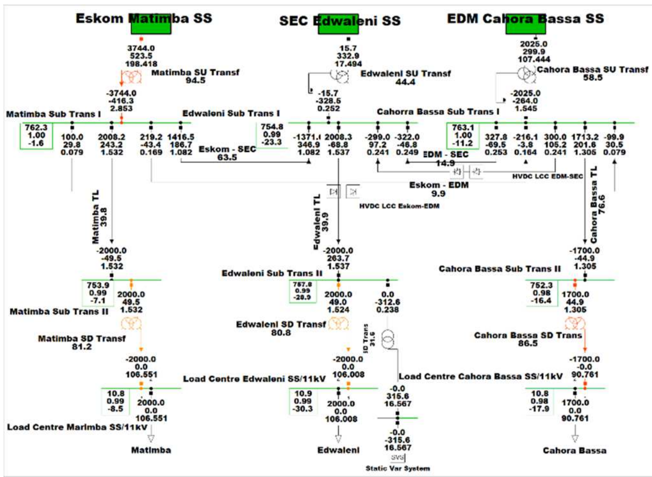

Fig. 10. The complete model of the three SAPP SS Power interconnection

The entire model is then run with the load demand, as shown in Fig.7, to conclude the usefulness of both the Static Var System and the HVDC LCC link in a network to optimizeand stabilize the system, as shown in Fig.10. The models wereused to examine the load flow when HVAC, HVDC, and FACTS devices, were used. The analysis was performed by altering the load of the three interconnected SS.Using this model, it is seen in Table II that the HVDC system has fewer electrical power losses when compared to HVAC and Facts devices.

TABLE II. POWER LOSSES FOR EACH MODEL

Name	Power loss (MW)
HVAC Load flow	101.70
HVAC With Static Var System	100.56
HVDC Load flow	85.53
HVDC Load flow With SVS	84.63

V. CONCLUSIONS

The models were constructed to study load flow when HVAC, HVDC, and FACTS devices were used, The investigation was conducted by altering the load on the three interconnected SS; it was discovered that when load demand increases, the grid's reliability decreases, Grid losses are avoided by the use of HVDC over the long transmission line (TL), and voltage is controlled with the SVC.

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