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Power Planning for a Smart Integrated African Super-Grid

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Abstract—**Africa's population has increased sharply from 364 million in 1970 to 1.3 billion in 2020 and is expected to reach 2.0 billion by 2050, representing the world's largest labor pool. Rapid growth in African population, generation capacity constraints, belated investment in new electricity infrastructure, load growth in unplanned areas, poor maintenance of existing power assets are some of Africa's critical challenges. These have resulted in demand outstripping available power generation capacity, leading to electricity shortages, load shedding, a huge backlog of unserved customers, and low economic growth. This paper presents the concept of a Smart Integrated African Super Grid, designed to energize Africa's emerging economy. In this paper, the five African Power pools are discussed, and the schemes for harnessing Africa's untapped renewable energy resources. A methodology is proposed to use highly complex power system controllers to integrate the African power pools, into a super-grid that absorbs large penetration of renewable powers using dispersed interconnected low voltage micro-grids, without compromising on power quality, stability, technical loss reduction, sustainability, and system reliability.**

Keywords—African power pool, power exchange, power interconnection, ultra-high voltage direct current (UHVDC) super grid, smart grids.

I. INTRODUCTION

Every aspect of human development has been proven over the last century to be woven around a sound and stable energy supply regime [1]. Apart from being stable, the energy produced in any country must be sustainable such that it meets the present needs without limiting future generations' energy needs. Thus, the concept of a stable and sustainable energy regime involves renewable, affordable, and clean energy while considering environmental and socio-economic effects. Africa's most urgent challenge today is scaling up energy capacity, a key condition for the United Nations sustainable development goal (SDG) agenda for 2030. Affordable and reliable power allows businesses and industries to effectively trade in the regional and global market, increasing economic growth, creating more jobs, improving livelihoods, and alleviating poverty. Africa's power generation capacity per capita is the lowest globally, and growth is declining. Thus, an integrated African power grid that is technically and economically feasible is the solution [2], using ultra-high voltage (UHV) DC transmission links over long distances, and smart grid technologies, to optimize its performance [3].

The smart integrated African super-grid overcomes the delivery limitations of traditional ac systems, unreasonable and unaffordable cost of power outages, low power quality, and inefficiency when managing peak load than the existing power grids [4]. A smart integrated African super grid is proposed in this study by integrating smart grid properties using existing network systems for efficient and reliable operation. High voltage direct current (HVDC) technology is the most applicable in the super grid for effective operation control, addressing intermittency issues in the generation, thus increasing the built-in redundancy incapacity [5, 6].

A power planning study for an integrated smart African super grid across the Africa continent with 55 countries is segmented into five regions: Northern Africa, Southern Africa, Western Africa, Eastern Africa, and Central Africa with a population of about 1.3 billion, approximately 46% population without access to electricity, the lowest globally, Sub-Sahara Africa consume about 180kWh per capita annual [7, 8]. Consequently, this study presents the existing Africanpower pools as backbones for the future African super smartgrid. The obtainable power interaction and the proposedsuper smart grid are outlined, and the conclusions are drawn.

The Northern African power pool (NAPP), also known as the Maghreb electricity committee (COMELEC), has the headquarters (H.Q.s) in Algiers, Algeria, with seven (7) countries relying on the abundance of oil and gas in the region. The southern African power pool (SAPP) with the H.Q.s located in Harare, Zimbabwe, consists of ten (10) countries and mainly depends on coal for power generation. The Western African power pool (WAPP), whose H.Q. is located in Lagos, Nigeria, comprises fifteen (15) countries [9], eight countries of which use diesel and heavy fuel generators to supply most of their electricity demand [10]. The Eastern African power pool has its H.Q.s located in Nairobi, Kenya consisting of fourteen (14) countries. Lastly, the Central African power pool (CAPP) has its H.Q.s at Libreville, Gabon, with an abundance of hydropower potential like Grand Inga in the DRC, which consists of nine (9) countries [1, 9, 11, 12]. African region electricity integration and support through grid interconnections and power pooling are a cost-effective way of ensuring the high security of the supply. Regional power pooling is the ultimate approach for dealing with the sparsely distributed energy resources and energy problems in Africa [13]. Power pools can be effectively operational in a region with developed grid interconnections and enough generating capacity to meet the pool demands. However, a sound electricity framework must be in place for cross-border electricity exchange besides mutual trust and confidenceamongst pool members [14]. Fig. 2 shows the data obtained from various sources [8, 15]to estimate Africa's total population and the installed capacity for the Africa continent.

II. OVERVIEW OF AFRICAN POWER POOLS

The need for interconnecting electric power systems acrossAfrica to curb energy insecurity and enhance synergies for social-economic cooperation resulted in five regional power pools, as shown in Fig. 1, at different development stages.

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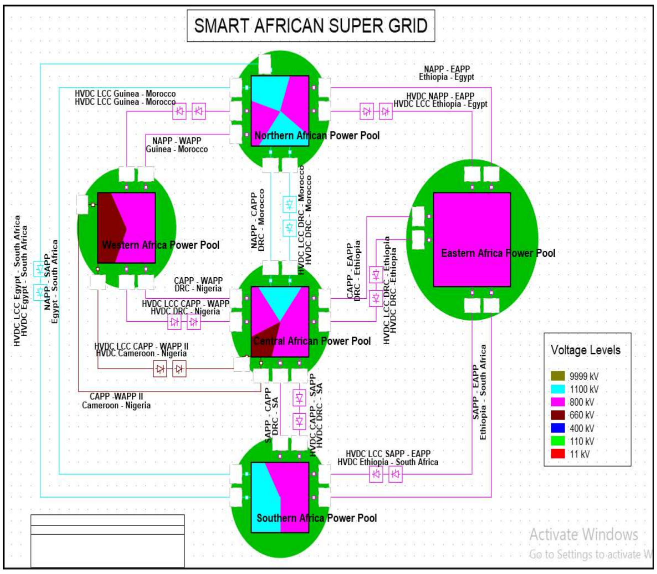

Fig. 1. Proposed African super smart grid.

A. *Five Africa Power Pools*

The Earliest NAPP interconnection was implemented in 1974 between Tunisia, Algeria, and Morocco. Currently NAPP has approximate 202 million populations with the installed capacity of 78GW, NAPP stands out as the highest in terms of the installed capacity in Africa. Egypt is the most populous with the greatest installed capacity [16]. The network interconnections and regional energy market integration would also allow economies of scale, regional expertise, and cost savings [1, 7].

The second Power Pool is SAPP which was established under the Southern African Development Community (SADC) in 1995 to provide a forum for regional solutions regarding electricity generation and supply via coordinated planning and the regional power system's operation [14]. Currently, SAPP has a population of around 180 million with an installed capacity of 68GW as illustrated in Fig 2. SAPP is the second after NAPP in terms of installed capacity. South Africa is the most populated country with the most installed capacity, with about 93% of electricity generated using coal [17].

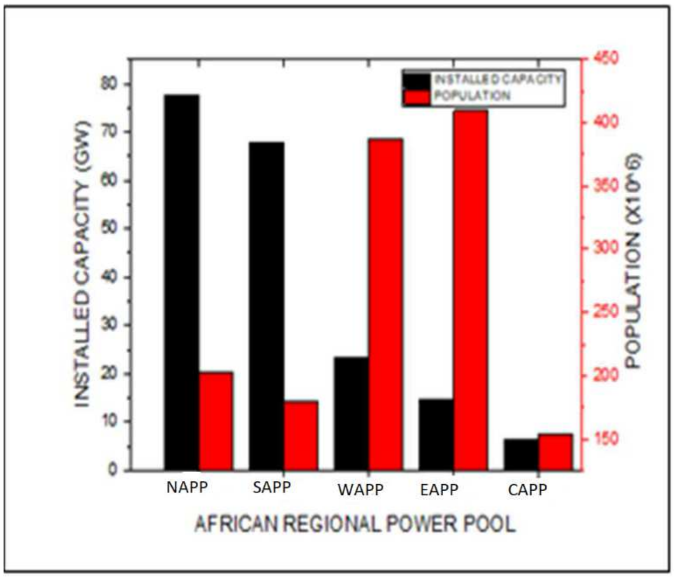

Fig. 2. Installed capacity & population for five African Power Pool.

The third Power Pool was recognized by the Economic Community of West African State (ECOWAS) between 2000 and 2001 to help sort out power supply shortagesin the West African sub- region. Currently, WAPP covers about 387 million populations with an installed capacity of 23GW shown in Fig. 2. Integrating the national power system's operation into sustainable and combined regional electricity trading is the WAPP vision to provide a steady and reliable electricity supply at reasonable prices to member states. Balancing the power supply and demand in every economic aspect is their objective while maintaining proper security and quality conditions [14, 18].

The fourth Power Pool is CAPP to support the Economic Community of Central African States (ECCAS). CAPP has nine countries. Currently, CAPP covers about 154 million populations with an installed capacity of 6.4GW, as in Fig. 2. The DRC has the greatest installed capacity with the most hydro potential to be harnessed, yet CAPP is the least in installed capacity. CAPP aims to promote power policies, improve regional power management, and trading in Central Africa [19].

The last Power Pool is EAPP which is the newest Pool, it was established in 2005 [14]. with the validation of anInter-Governmental Memorandum of understanding (IG- MOU) amongst the seven Eastern Africa countries shown inFig. 2. Currently, EAPP has about 410 million populations with an installed capacity of 15GW. EAPP has had increasing membership, with Ethiopia having the highest installed capacity and population and Comoros with the leastin each case. It covers more than 515 million people and stands out as the region with the largest population growth rate.

B. *Power interconnection*

Five power pools were first connected in their region, using their countries as synchronous generators to produce power within their region, the reserve power will be transmitted to other Power Pool that lack power demand as shown in Fig. 3 the HVDC in this case Line Commutated Converter (LCC) will be constructed to support High Voltage Alternating Current (HVAC) side of the system in long distance transmission line.

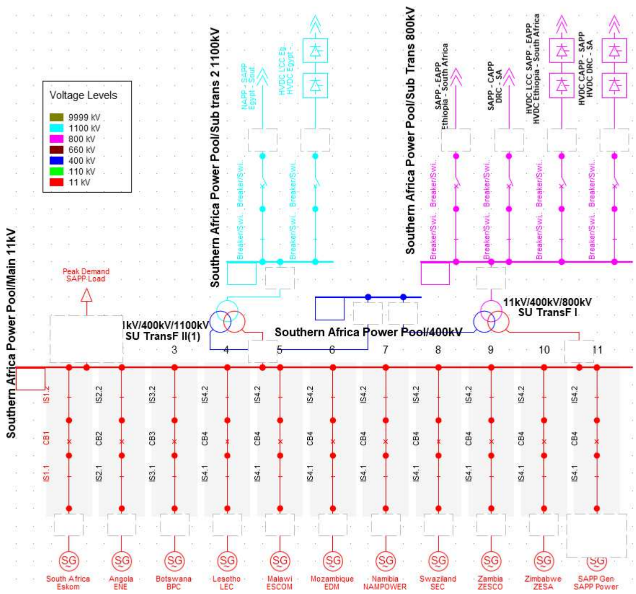

Fig. 3. Southern Africa Power Pool proposed network

III. CURRENT AND PROPOSED AFRICAN POWER GRIDS INTERCONNECTIONS

Most of Africa's power systems are typically traditional in architecture and operation-control. Electricity flows to consumers from power plants. These kinds of systems are environmentally burdensome and consume lots of fossil fuels like coal and oil. The power grid is also not flexible enough to acquire the adequate capacity to meet future demand [20]. The current power grid contributes greatly to the global warming effect that results in a negative environmental impact. There is a need to tap the abundant renewable energy sources in Africa that is pollution-free, environmentally sustainable, and technologically effective. The current transmission and distribution network is regarded as a 'dump' system because it cannot give the intelligent data required for modern grid operation. Additionally, the current power grid cannot offer satisfactory service for energy efficiency, security, and reliability of integrating renewable energy with the scale in need to meet the clean energy demand. Therefore, the smart super grid's proposal solves all these problems[21, 22].

African regional power integration and cooperation is a cost-effective way of ensuring reliable supply. The regional power pools are recognized as the best strategy to deal with Africa's unevenly distributed electricity resources and electricity access problems [14]. The CAPP has abundant hydropower of about 1057 TWh potential for power generation, 1572 TWh biomass. NAPP has 1090 TWh from solar photovoltaic (P.V.) and concentrated solar power (CSP) 935 TWh, and also with 1014 TWh wind potential, WAPP has 1038 TWh potential from P.V. EAPP is with 2195 TWh P.V. potential, 1758 TWh CSP and 1443 TWh wind potentials. Lastly, SAPP has 1500 TWh, 1628 TWh, and 852 TWh power potentials for CSP, P.V., and wind, respectively [23]. Africa's integrated power system is the optimal way of managing the inter-regional multi-energy complementation to overcome regions with environmental, economic, and energy security disadvantages [24].

A. *Proposed African Smart Super grid*

The proposed African super smart grid intends to comprise highly complex power system controllers to integrate existing African power grids into a super-grid that can admit large penetration of renewable power without compromising power system stability and power reliability. This projected super grid will be assembled with ultra-high voltage Alternating Current, and direct current (UHVAC and UHVDC) besides flexible ac transmission systems (FACTS) along with dedicated A.C. and D.C. interconnectors with intelligentsystem applications to create an integrated African super smart-grid [7].

Fig. 2 is the proposed African super smart grid showing the interconnection amongst the five African power pools. Such as± 660kV,8GW, 1100 km, DRC-Ethiopia DC project, ± 1100kV, 8GW, 8000 km, South Africa-Egypt, ± 800 kV, 8 G.W., 2800 km Ethiopia-South Africa DC project (SAPP – EAPP), ± 800 kV, 8 G.W., 3800 km DRC- South Africa DC project (SAPP –CAPP), ± 800 kV, 8 G.W., 4000 km DRC-Ethiopia DC project (CAPP –EAPP), ± 1100 kV, 8 G.W., 6500 km DRC-Morocco DC project (CAPP – NAPP), ± 800 kV, 8 G.W., 2000 km DRC-Nigeria (CAPP – WAPP), and ± 800 kV, 8 G.W., 1900 km Ethiopia-Egypt DC project (NAPP – EAST) and further a proposal of± 800 kV, 8 G.W., 3800 km Guinea-Morocco DC project (NAPP – WAPP) [3].

– EAST) and further a proposal of± 800 kV, 8 G.W., 3800 km Guinea-Morocco DC project (NAPP – WAPP) [3].

B. *UHV & HV (AC and DC) interconnection*

The UHVDC, HVDC, A.C. & D.C. interconnectors will segment the entire continent's power system into five large asynchronous segments, originally the regional power pools. The asynchronous segments will avert A.C. fault propagation among segments while allowing power exchange between different parts of the super-grid, withminimum difficulty for grid code unification or harmonization of regular design regimes across the continent as each segment preserves its autonomy. An Integrated African Electrical Power Super-Grid driven by smart grid technologies is central in supporting Africa's sustained economic growth and development. This is built on the cornerstone of green energy and harnessing about 200GW untapped potential of Africa's hydro-electric power,solar-PV, and wind power as a share of a vast energy mix made of conventional and alternative energy resources. The proposed super smart grid will energize Africa's emerging economy, serve its 1.3 billion people, foster electricity trading and power exchange amongst the five regions with 55 countries [25].

The long-distance transmission network HVDC is extra economical compared to HVAC. HVDC is strongly recommended to facilitate cross-border interconnections to benefit Africa from the large-scale renewable energyprojects [26]. The advantages of HVDC over HVAC are in [27, 28] such as connections of asynchronous grids, lower transmission losses in long distances. The large network will be of HVDC, interconnected by D.C. cables equipped by DC-DC converters. No fast-acting D.C Circuit Breakers (DCCBs) will be used in the D.C. network to reduce cost and power loss [27, 29].

UHVDC is mostly used over large-scale networks due to longer transmission networks and larger power transmission capacity than conventional HVDC systems. Long transmission lines upsurge D.C. line faults' probability dueto a tough operation environment [30].

IV. NETWORK PLANNING & SETUP

The network was built and simulated using DIgSILENT PowerFactory software tool with the aim of analyzing UHVAC and UHVDC load flow and power transfer capacity across the entire Africa region with the help of Newton-Raphson's method and other equations and other constraints to ensure the reliability of the grid such as that, the bus voltage must be within the limit of 95% and 105% of its nominal range as shown in Fig. 4, the grid system must be able to withstand loss of the generator and transmission line, its generating capacity must be greater than its peak demand and overload on generators, loads and transformers must be prohibited, below is the apparent power equation for nonlinear circuit.

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

Where

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

The real P_i and reactive Q_i powers for each bus in a power network are obtained by [31].

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

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

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

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

For HVDC LCC link, the DC Current is as follows:

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

Whereby

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

Using the rated V_{ac} to get V_{dc} of the DC link

V. Model Building and Simulation Results

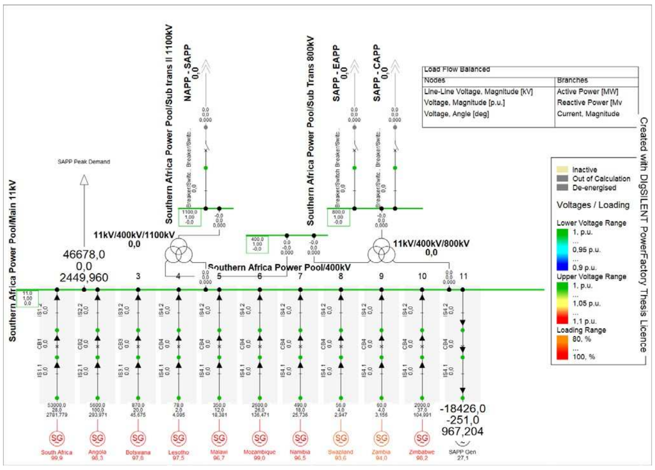

Fig. 4. Southern Africa network model

In order to carry out the simulations, a network was built on the software tool DIgSILENT PowerFactory, the data was previously collected, the model network of each Pool was built individual, representing the substation to observe the generating power compared to the demand of each pool when they operating as individual pool, and later interconnected together using Ultra HVAC and Ultra HVDC power interconnectors. All the generating units for each Power Pool were connected to one busbar, each country of the pool representing its generator capacity, such as Fig. 4, above showing 10 countries of SAPP connected to a busbar to form one Mega substation, generating 65.104 GW with the peak demand of 46.678GW and the reserve power of 18.426GW. the network building was done to all the five power pool and the loading range of the generators were restricted within the range of (80% -100%)

Table 1 was constructed using software's output to identify nations that will benefit from power exchange; it includes the total producing capacity of each pool running at 80% -100% of the installed capacity.

TABLE I. POWER POTENTIAL EXCHANGE

Pool Name	Active Power (MW)	Power Demand (MW)	Power reserve (MW)	Power shortage (MW)
SAPP	65101	46678	18426	-
CAPP	56624	26101	30523	-
WAPP	22097	26600	-	4503
NAPP	77326	63126.5	-	14199.5
EAPP	14522	53000	-	38475

The entire network model was developed, once again utilizing the PowerFactory Software tool, with the goal of forming one African Super grid for the purpose of power exchange with the pool's disadvantage countries, such as most countries in the WAPP and EAPP that lack access to electricity. The locations targeted for power transfer include the Inga dam in the DRC's CAPP, which contains an abundance of hydropower estimated to be roughly 53GW, and the SAPP, which contains an abundance of coal expected to account for approximately 93 percent of SAPP-generated electricity.

A. *African Super Grid*

Upon completion of the individual network of Five region, the model was then interconnected using ultra-HVAC to transfer power to other pools lacking electricity as show in Fig. 5, with SAPP transmitting 15683.2MW to EAPP which 699.3MW of that power was exported from CAPP to SAPP, again SAPP is exporting 3441.5MW to NAPP which leaves SAPP with no reserve.

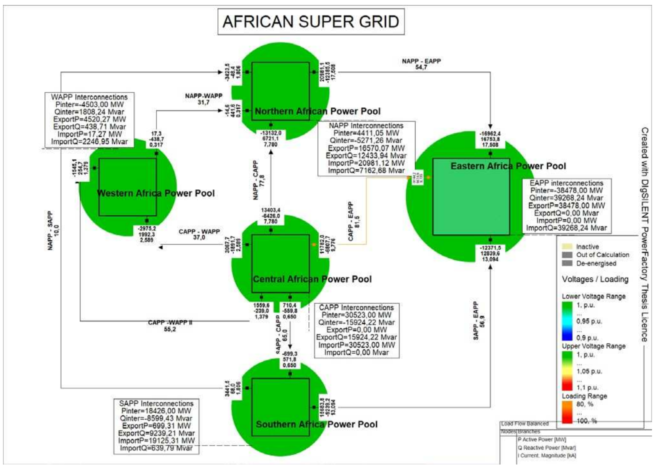

Fig. 5. African Super Grid with HVAC transmission line

In Fig. 5, The losses of HVAC in the lines were considered asshown in SAPP-CAPP line where 710.4MW is exported to SAPP and 699.3 MW is received in the SAPP.

B. *African Super grid transfer capabilities*

The transfer capacity analysis was conducted on DigSILENT PowerFactory to observe the total transfer capacity (TTC) for the last feasible solution of each pool with the restof the network, the model in Fig. 6 shows the transfer capacity analysis in the CAPP to the rest of the network.

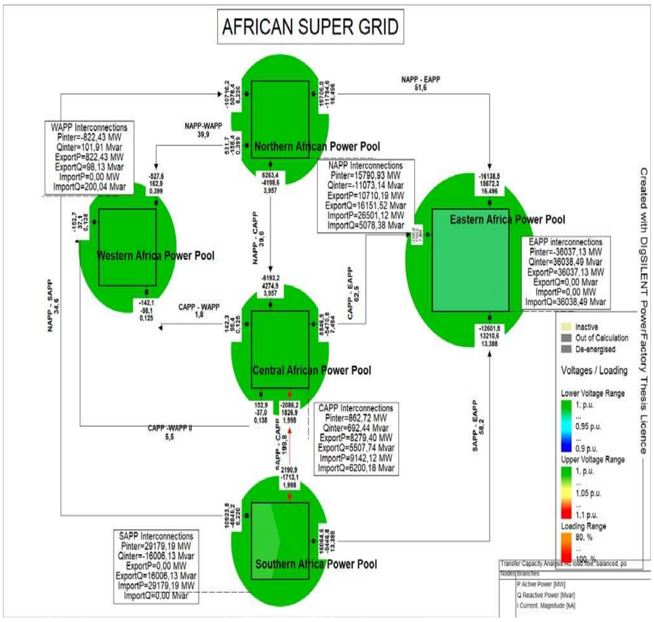

Fig. 6. CAPP maximum Power transfer capacity model

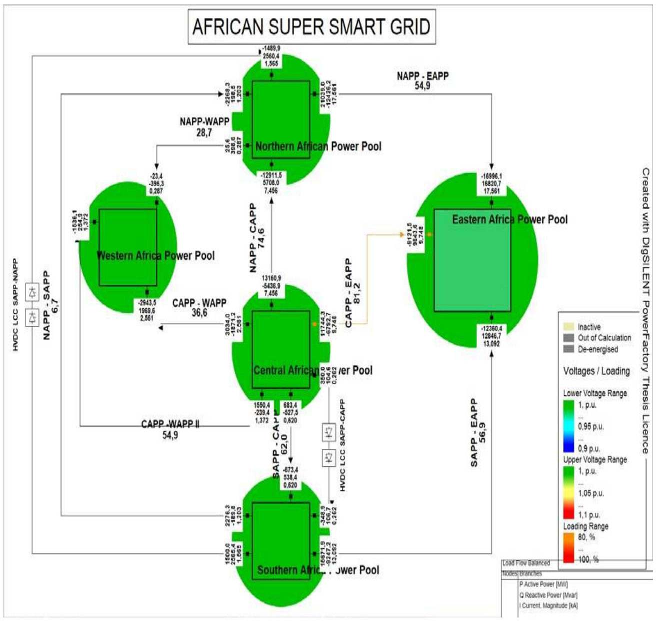

Fig. 7. Smart African Super Grid Model network

As illustrated in Fig. 6, CAPP is capable of importing 9142.12MW to EAPP and WAPP and exporting 8279.40MW to NAPP and SAPP. As stated in Table II, CAPP has a maximum TTC of 3108MW.

Table II was constructed based on the analysis of determining the maximum feasible power flow between two parts of the network which in this case is each pool compare with the rest of the network by scaling demand or generation in the opposite direction in the two parts, it is basically illustrate the total transfer capability limit for each pool to the rest of the network.

TABLE II. POOL MAXIMUM TRANSFER CAPABILITIES

Region Power pool – African Super grid	Maximum Total transfer capacity (TTC) (MW)
SAPP	4343,02
NAPP	20735,28
WAPP	1318.73
EAPP	4630.58
CAPP	3108

C. African Super Smart Grid

The African super smart grid was constructed using HVDC LCC link to control the DC power in order to control the AC power, the DC link is capable of helping and support the AC side of the network, the DC link have several controllers that are set in order to enhance the features and the capability of the system, in Fig. 7 two DC link are planted in this network to enhance the power between CAPP –SAPP and SAPP-NAPP to illustrate the results of HVAC side with the help of HVDC compared with original HVAC values on Fig. 5.

The DC power set points for CAPP – SAPP and SAPP – NAPP were initially set to 350MW and 1500MW, respectively, and the results are summarized in Table III. The DC power set points were then altered to analyze the behavior as illustrated in Table III.

TABLE III. COMPARISON OF THE TWO NETWORK MODELS

Power set point (MW)	AP on AC Before HVDC (MW)	AP on AC after HVDC (MW)	AP on HVDC LCC link	Enhanced AP
CAPP – SAPP				
350	710,4-699.3	672,9-663	350-348.9	1011.9
710		629,6-621,1	710-705.4	1326,5
SAPP - NAPP				
1500	3441,5-3423,5	2276.3-2268.3	1500-1489.9	37758.2
2000		2049.,9-2043.3	2000-1982,2	4025.5

The projected African super grid envisions a continent with very high access to electricity at an affordable cost, employing a range of generation technologies. Thus, the electricity infrastructure can be robust, sustainable, efficient, and reliable. This will facilitate power exchange among regional power pools, which will benefit nations that are electricity deficient. Fig. 7, and Table III demonstrate that by utilizing HVDC over long distances, power transmission capacity is increased, which strengthens the grid.

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