Asynchronous Interconnection of the Proposed East Africa Power Pool (EAPP)

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Abstract: East Africa Power Pool (EAPP) is a proposed regional interconnection for centralizing energy resources and facilitating power wheeling between the Eastern Africa geographical areas. Synchronous tie lines have been used in the established interconnections so far. However, asynchronous interconnection is preferred since there high Renewable Energy (RE) penetration in the EAPP. HVDC technology, particularly multi terminal DC (MTDC) is a good example of such links as it provides loose coupling between the interconnected power systems. This has several economic ,environmental and security-stability merits as compared to the traditional HVAC tie lines. The Kenya-Ethiopia HVDC Bipolar is supposed to provide a loose coupling between the two countries. The same technology can be reproduced in the EAPP so as to achieve a dynamic regional interconnection. Thus, a 10-Area system with 18 MTDC tie lines is considered where each area represents a Transmission System Operator (TSO) for each country. In this paper, a multi area multi objective economic dispatch (MAMODED) with RE and Emissions is formulated where MTDC constraints have been included for the first time in the EAPP. Review of EAPP and MAMODED with RE, merits of MTDC interconnection, RE penetration in EAPP, and MTDC tie line power flows are also presented.

Key Words: Asynchronous Interconnection, East Africa Power Pool (EAPP), Multi Area Multi objective dynamic economic dispatch (MAMODED), Multi Terminal DC (MTDC), Renewable Energy (RE), Transmission System Operator (TSO)

I: INTRODUCTION

There is increased need for interconnecting power systems in the world because multi area power systems have economic, security and environmental advantages [1, 9]. These merits have led to the emergence of various power pools in Africa. There are four regional power pool in Africa which are at different stages of development. These can be summarized as in Table 1.0. The table shows the name of the pool, member countries, the level of power exchange and the region. From the table, it is apparent that power pooling is more developed in WAPP, COMELEC, and SAPP as compared to EAPP and CAPP. Thus, this paper will concern itself with the regional interconnection ties and generation in the EAPP.

Contribution: The EAPP interconnection is considered for the first time with increased RE penetration and asynchronous interconnection (MTDC tie lines). All the possible member states are considered in the multi area multi objective dynamic economic dispatch (MAMODED) formulation.

Paper Organization: The rest of the paper is organized as follows: Section II is the EAPP in perspective, Section III is the review of interconnected systems with RE, Section IV highlights the merits of the proposed asynchronous interconnection, Section V is the formulation of EAPP-MAMODED with RE, Section VI is EAPP interconnection layout and area and finally Section VII is a conclusion and proposed future work and research

TABLE 1.0: REGIONAL POWER POOLS IN AFRICA

Power Pool	**Countries**	**Power Wheeling**
COMELEC	Algeria, Libya , Morocco, Mauritania and Tunisia	5%-6%
SAPP	Angola, Botswana, Lesotho, the DRC, Lesotho, Malawi, Mozambique, Namibia, South Africa, Swaziland, Tanzania, Zambia and Zimbabwe.	6%-15%
WAPP	Benin, Burkina Faso, Cape Verde, Ivory Coast, Gambia, Ghana, Guinea Bissau, Liberia, Mali, Niger, Nigeria, Senegal, Sierra Leone and Togo.	6.9%
CAPP	Angola, Burundi, Cameroon, Chad, Congo, Gabon, Equatorial Guinea, Central African Republic, Democratic Republic of Congo and Sao Tome.	Min
EAPP	Burundi, DRC, Egypt, Libya Ethiopia, Kenya, Rwanda Uganda, Tanzania and Sudan	Min

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II: EAST AFRICA POWER POOL (EAPP)

The Eastern Africa Power Pool (EAPP) was proposed and established on 24 February 2005 with the signing of an Inter-Governmental Memorandum of Understanding (IG-MOU) by the Energy Ministers of seven countries. It is a framework for centralizing energy resources and promoting power exchanges (pooling) between utilities in the Eastern Africa geographical area based on an integrated master plan and pre-established interconnection rules. The member countries are as shown in Figure 1.0.They include Kenya, Uganda, Tanzania, Rwanda, Burundi, Libya, Egypt, Sudan, Ethiopia and DRC [10]

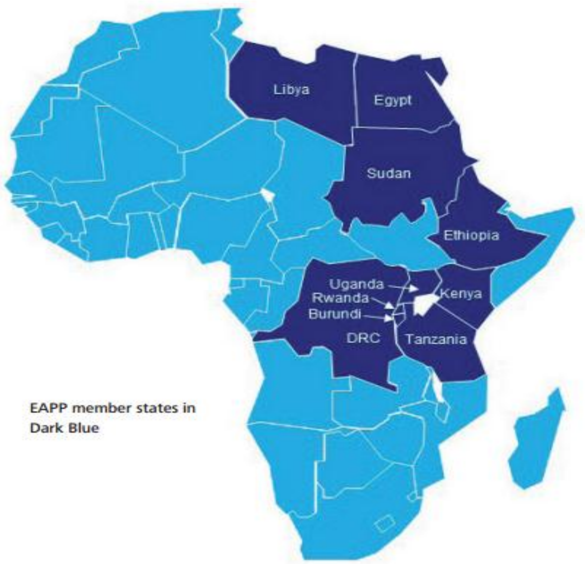

Figure 1.0: EAPP Member Countries [7]

A: Objectives and Benefits of EAPP

The major objectives of EAPP include the following [2]: (i) To provide secure and stable power supply for the EAPP member countries.(ii)To ensure optimal utilization of energy resources available in the EAPP Region by working out EAPP regional investment schemes in Generation, Transmission and Distribution, taking into account the socio-economic and environmental aspects. (iii)To coordinate and co-operate in the planning, development and operation of the power systems at minimized costs. (iv)Increase power supply in the EAPP Region in order to increase access rate of the population to electricity. (v)To reduce power cost in the EAPP region by using power systems interconnection and increasing power wheeling between countries. (vi) To play its role for coordination between various initiatives taken in the fields of power production, transmission as well as exchanges between countries. (vii) To create in the framework of NEPAD, a good environment for investment so as to facilitate financing of the integration projects in the fields of power generation and transmission in the EAPP Region. (viii) To facilitate the development of a competitive electricity market in the EAPP region based on co-operation among the member countries, transparency and respect for the environment.

The overall benefits of EAPP to its members include the following to: (i) Secure reliable power supply through regional market, promote mutual assistance in case of failure in their respective power system (ii)Provide social, economic and environmental benefits since RE is clean (iii)Reduce capital and operating costs through improved generation, transmission expansion and coordination among power utilities (iv) Optimize generation of power with large units, improve power system reliability with reserve sharing, improve investment climate avoiding power shortage risks, build trust, gradually clean grudges, minimize idiosyncrasy of hatred and strengthen cooperative relationships among the member countries.

In summary, EAPP will benefit the members in reduction of the following[10]: operation costs due to economic power exchange, investment costs in additional generating capacity due to least-cost development of energy resources from a regional as opposed to a national perspective and sharing reserve requirements as a proportion of peak load. These benefits thereby will improve reliability and security of energy supply. Improvement of supply reliability and security of electricity can guarantee different economic and social service sectors to expand as well as invite more investments. Therefore, for the region's governments harnessing their available energy resources and exporting power through integrated system is a Pan-African call of the moment to conquer backwardness as well as negotiate on their differences to create peace with themselves and others. These benefits will be realized if the hurdles of the implementation are overcome and solved. Next, we consider the challenges of realizing a fully operational EAPP.

B: Challenges of Implementing EAPP

In [5], Deloitte highlights the benefits of power pools as well as the critical success factors that must be addressed if the salient EAPP is to be translated into a fully integrated and operational power pool premising upon the evolutionary experience of some of Africa's earlier power pools(that is, COMELEC, SAPP,WAPP and CAPP) and Nordel. Nordel is a regional organization of the Transmission System Operators (TSOs) of Nordic countries. It represents a well-operating, robust regional organization set up that has evolved through all phases for almost 40 years, underpinning the development of a common Nordic electricity market. It is considered as a model for multi country power pooling mechanisms.

These success factors in [5] include Legal and regulatory framework, Harmonization of legal and operational framework, Increasing power generation capacity, Bilateral and multilateral agencies, Independent regional regulator, Designing a regional power trade market and Cross border interconnection facilities. This paper concerns itself with increasing generation using RE and the challenges of the synchronous interconnection in the EAPP master plan and proposing the need for asynchronous ties. All these are considered with high RE penetration in the pool. Thus, review of multi area multi objective dynamic economic dispatch (MAMODED) with RE is considered in the next section.

III: MAMODED WITH RENEWABLE ENERGY

With RE penetration, the power pooling mechanism changes drastically, EAPP is such a case. Hence, there is need to review regional interconnection in presence of RE. Three recent works have considered multi area economic dispatch (MAED) with renewable energy (RE).

In [6], a MAMODED incorporating hydrothermal, wind and a power reserve market is considered. Scenario-based method (SBM) is adopted for uncertainty modeling and optimality condition decomposition (OCD) is used in the solution process. The two-method hybrid approach demonstrates the real-time scheduling of joint thermal systems with undispatched wind energy in a 3-area and 5-area multi area system. In [7], a penalty function-hybrid direct search method (PF-HDSM) is further employed for the solution of a multi-area wind-thermal coordination dispatch problem. In [8], security and control areas of MAMODED with wind and solar REs were addressed. In [12], P. Musau et al considered a fully constrained MAMODED with wind and solar. The thermal, tie line losses and emissions objectives were modelled using the relatively more accurate cubic cost functions. A three-method hybrid called Modified Firefly Algorithm with Levy Flights and Derived Mutations (MFA-LF-DM) is utilized.

A: Limits of Synchronous Interconnection Ties

In the works contained in [6]-[8] and [12], synchronous (HVAC) interconnections have been utilized. HVAC tie line provides a *rigid connection* between any two areas. Even with coordinated control of the AC areas, the operation of the HVAC tie line suffers from three technical problems [3], that is, transfer of disturbance between areas, cascading of power swings resulting into frequency tripping and increased fault levels. These draw backs necessitate the need for asynchronous interconnections in practical power pools like the EAPP considered in this paper.

IV: PROPOSED EAPP ASYNCHRONOUS INTERCONNECTION

In [9], HVDC (MTDC) interconnection was implemented the first time for MAMODED with RE, 5 areas and 8 tie lines. Since HVDC tie lines provide a *loose coupling* between the two interconnected areas. Such interconnection is referred to as non-*synchronous (asynchronous) tie line*. This interconnection has several merits [3,9]:(i) Interconnection of AC systems at different frequencies is possible to enable such operate independently and maintaining their frequency standards at the same time (ii)There is fast and reliable control of power flow by controlling the firing angle of the converters, that is, the Converter Ignition Angle (CIA) and the Converter Extinction Angle (CEA) (iii) There is rapid damping of power swings by modulating the power flow through the HVDC lines, thus increasing the stability of the overall system (iv) There is no fault transfer between the areas.

A multi terminal DC (MTDC) has more than two converter stations and interconnecting DC transmission lines, thus it is the HVDC system of choice for the multi area asynchronous tie lines in this paper because of [3,4,9]: (i) Flexibility and economic merits (iii)Fast damping of oscillations (iii) Inherent overload capability without instability (iv) Reinforcement of overloaded AC areas concerned. Next we consider EAPP with MTDC problem formulation.

V: EAPP-MAMODED WITH MTDC AND RE FORMULATION

The problem remains as formulated in [9] except that the tie line cost function is modified to accommodate EAPP specifications. In this paper, a MAMODED with RE and Emissions for the 10 areas (each area representing the EAPP member countries) is formulated where MTDC interconnections will be utilized. The MAMODED formulation can be given as

$$\min f = \sum_{m=1}^{10} \{W_1 F + (1 - W_1)E\};\ \ 1 < m \ < 10 \quad (1)$$

where W_1 is the weighting factor between the fuel cost (F) and emissions (E). The total operational cost (F) for MAMODED with thermal and RE (DFIG and PV) units, tie line losses and emissions is given as

$$F = \left[F\left(P_{i,m}\right) + F\left(w_{ijm}\right) + F\left(PV_{ijm}\right) + F(T)\right] \quad (2)$$

The merits of MTDC interconnection, technical challenges, power and emission exchanges will be investigated.

The problem remains as formulated in [9] except that the tie line cost function is modified to accommodate EAPP specifications contained in the master plan [2].

Asynchronous (MTDC) Tie Line Losses Cost Function (ATLLCF): The transmission cost in MAMODED for power transfer EAPP countries using MTDC tie lines is expressed as

$$F(MTDC) = \sum_{m=1}^{9} \sum_{k=m+1}^{10} f_{mk}\, T_{mk} \quad (3)$$

where T_{mk} is the MTDC tie line from area m to k , f_{mk} is the transmission cost coefficient relevant to T_{mk} and T is the vector of real power transmission between the countries.

MTDC Constraints

- MTDC Transmission Capacity Limits (MTCL):The transfer including both generation and reserve from area m to k should not exceed the MTDC tie line transfer capacities for security considerations .This can be expressed as

$$T_{mk,min} \leq T_{mk} + R_{mk} \leq T_{mk,max} \quad (4)$$

where $T_{mk,min}$ and $T_{mk,max}$ represents the MTDC tie line transmission capability.

- MTDC Tie Line Flow Constraint(MTLFC)

$$|P_{tmk}| \leq P_{t,max}\ t = 1,2,3 \dots \dots ..10 \quad (5)$$

where N_t the number of is tie lines and P_t is the active power flow in the tie line t

- MTDC Converter Tap Ratio Constraint (MCTRC)

$$T_{mk,min} \leq T \leq T_{mk,max} \quad (6)$$

- MTDC Converter Ignition Angle Constraint (MCIAC):Facilitates fast and reliable control of power flows

$$\alpha_{mk,min} \leq \alpha \leq \alpha_{mk,max} \quad (7)$$

- MTDC Converter Extinction Angle Constraint (MCEAC):Facilitates rapid control to increase transient stability limit

$$\gamma_{mk,min} \leq \gamma \leq \gamma_{mk,max} \quad (8)$$

- HVDC Current Constraint (HCC)

$$I_{dc,mk,min} \leq I_{dc} \leq I_{dc,mk,,max} \quad (9)$$

- HVDC Voltage Constraint (HVC)

$$V_{dc,mk,min} \leq V_{dc} \leq V_{dc,mk,max} \quad (10)$$

VI: EAPP INTERCONNECTION

A: EAPP Power Generating Capacity

The region is presently faced by power capacity shortages. Unless there is investment undertaken to generate sufficient power that can cater for both the domestic and export needs, the envisioned EAPP shall not take off. A study commissioned by the East African Community whose report was issued in 2011 identified a number of regional power generation projects that could be undertaken to tackle the challenge of power supply shortages in the region both in the short term and in the long term. These generation projects blend hydropower, nuclear, geothermal and thermal sources. The investment requirements to realize this aspiration are substantial and will require the participation of private investors to help each country achieve its projected generation capacity. Attracting private investment calls for a review of the fiscal and legal regimes to create the most favorable environment. It is anticipated that investment in these projects will enhance generation capacity as shown in Table 2.0[5]. The symbols in the table can be defined as A: Area (m), E: Existing MW, P: Projected MW (2017-2030), T: Total MW by 2030, D: Demand MW by 2030 and S: Surplus MW (Available in the MTDC tie lines). This anticipated generation will be realized by full exploitation of the non-conventional sources of energy (RES)

TABLE 2.0 PRESENT AND FUTURE EAPP GENERATION CAPACITY [10]

A	Name	E	P	T	D	S=T-D
1	Kenya	3,100	7,290	10,390	7,800	**2,590**
2	Tanzania	1,260	6,100	7,360	3,800	**3,560**
3	Uganda	890	3,600	4,490	2,100	**2,390**
4	Rwanda	155	520	675	550	**125**
5	Burundi	90	530	620	405	**215**
6	Sudan	4,050	12,100	16,150	11,500	**4,650**
7	DRC	130	2,200	2,330	205	**2,125**
8	Libya	4,700	10,500	15,200	2,100	**13,100**
9	Ethiopia	2,300	14,800	17,100	8,500	**8,600**
10	Egypt	26,100	47,500	73,600	70,100	**3,500**

B: Renewable Energy In Various States in EAPP Model: Scenario-Based Method (SBM)

In this paper, states are generated by Roulette Wheeling Method (RWM) and modelled by Scenario-Based Method (SBM). High RE penetration in EAP demands state modelling of the RE in various scenarios. For a multiple variable function ,$y = F(X)$ where X is a vector containing the uncertain input values, the SBM uncertainty representation is aimed at determining the expected value of y. A set of scenarios, Ω_s, is generated for describing the probable (possible) values of X such that [9];

$$y = \sum_{s\epsilon\Omega_s} \pi_s F(X_s) \qquad (11)$$

where π_s is the probability of state s. The RE (wind, w and solar, s) in various states in the EAPP are given in Table 3.0. In this case, $w_{ij,s}\%$ and $PV_{ij,s}\%$ represent the percentage penetration of wind and solar resources in each state. The trend repeats itself in the higher states.

TABLE 3.0: RENEWABLE POWER IN VARIOUS STATES

States Ω_s	$w_{ij,s}$ %, $PV_{ij,s}$ %	$\pi_{s,w}$[12]	$\pi_{s,s}$[12]
1	0	0.3045	0.4080
2	5	0.1811	0.1018
3	15	0.2323	0.2584
4	20	0.4029	0.8968
5	35	0.4125	0.6826
6	45	0.1809	0.2910
7	55	0.1876	0.1079
8	65	0.1608	0.3105
9	75	0.1350	0.2668
10	85	0.1213	0.1005
11	95	0.1148	0.1316
12	100	0.1666	0.5277

Uncertainties and variability in RE power generation, reserve market prices and load profile of the system, emerge into a probabilistic EAPP which is formulated in this paper. The total cost of energy procurement at any instant in the EAPP is given by

$$C_T = \sum_{S,t,m} \pi_s PP_{s,m}(t)\lambda_s(t) + \sum_{i,t,m} C_{im}\left(P_{im}(t)\right) \quad (12)$$

where C_T is the total cost paid by the retailer (or TSO), π_s is the probability of scenario s, $PP_{s,m}(t)$ is the purchased power from reserve market in time t ,scenario s and area m, $\lambda_s(t)$ is the price of energy purchased from the power reserve in time t ,scenario s($/MWh) and $C_{im}(P_{im}(t))$ is the production cost of the i^{th} thermal unit located in area m in time t.The objective function of a rational retailer that is to be maximized is defined by

$$F = \sum_{S,t,m} \pi_s P_{D,s,m}(t)\lambda_c(t) - C_T \qquad (13)$$

where $\lambda_c(t)$ is the price of energy sold to customers in time t, and $P_{D,s,m}(t)$ is the load demand at time, scenario s and area m. In the EAPP, power cost is dynamic in that it depends on the RE available in the particular scenario, power loss in the MTDC lines and the traditional wheeling costs considered in most literature.

C: Proposed Asynchronous Tie Lines for EAPP

The proposed MTDC power flows and the respective voltages are as shown in Table 4.0. Some of these tie lies are operational in the synchronous mode while other are under development. Numbers 1 to 10 represents the areas as shown in Table 2.0. The asynchronous mode of the operation is the main objective of the proposed study.

TABLE 4.0: EAPP MTDC TIE LINE FLOWS

MTDC Tie Lines	Power(MW)	Voltage(KV)
T_{1-2}	1,000	400
T_{1-3}	500	220
T_{1-6}	1,500	-
T_{1-9}	2,000	500
T_{2-3}	1,000	-
T_{2-4}	1,000	220
T_{2-5}	1,000	220
T_{2-7}	1,000	-
T_{3-4}	500	220
T_{3-6}	1,500	-
T_{3-7}	1,000	-
T_{4-5}	200	220
T_{4-7}	250	220
T_{5-7}	250	220
T_{6-8}	2,500	-
T_{6-9}	3,500	500
T_{6-10}	2,500	600
T_{8-10}	3,500	-

VII: CONCLUSION AND FUTURE WORK

The need for regional interconnection in Africa is paramount. This paper has provided a background towards the formulation and solution of a practical multi area problem (EAPP) with RE penetration. First, the need for regional interconnection has been revisited and the objectives of EAPP reviewed. Merits of asynchronous interconnection using the HVDC technology has been reviewed and compared with the traditional HVAC tie lines. EAPP-MAMODED has also been formulated incorporating the MTDC constraints. The present and future generation capacity and the RE in various states have been presented. The MTDC tie line specifications have been given. Further work will consider a methodology for handling the Asynchronous EAPP, the power wheeling in terms of cost and emission levels and a validation of the

MTDC technology as compared to the synchronous. The three-method hybrid proposed in [9] and [12] will be applied in the solution of the problem. Further, to make the proposed interconnection feasible, the technical challenges of Protection, Transformers, Converter Stations Cost, System Cooling, Overall efficiency and Control of MTDC will be addressed [11]

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