Voltage Collapse Assessment in Developing Countries EHV Cross-Boundary Interconnection: A Case Study

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***Abstract* — The development of the Lufubu Hydropower Cascade Project in Zambia comprises three cascade plants totalling 326 MW (Phase 2). The project is being promoted by the Lufubu Power Company (LPC) a private Zambian company which, with the support of consulting engineers Studio Pietrangeli (SP) that developed the design and the environmental and social impact assessments (ESIA), and the transaction advisors Fieldstone South Africa.**

The paper presents the main technical features of the project, its interconnection to the national grid as well as methodology and results of the voltage stability analysis, performed in CYME PSAF environment, of the Zambian power system with the target year 2030. The study is part of the feasibility design for the Lufubu Hydropower Cascade project development, carried out by SP, with the scope of assessing system operation behaviour synchronously interconnected with the neighbouring countries as the DR Congo, Tanzania, Malawi, Mozambique, Namibia, Angola, Zimbabwe and within the South African Power Pool (SAPP).

Keywords—Transmission system, voltage collapse, voltage stability margin, proximity indicator, stability analysis, power flow, security assessment, system operation, SAPP, Zambia, Tanzania, cross-border corridor, hydropower

I. Introduction

The Northern Province of Zambia is a predominantly rural province, with agriculture being fundamental for the population's livelihood. The province has lagged behind in terms of development due to poor and inadequate growth-enhancing infrastructure and access to social services that have posed a challenge for development.

At the time of this study (2014 - 2015) [1], the Zambian national grid still applied an extensive plan of load shedding since the previous decade, mainly due to the inadequacy of the existing electricity generating capacity and the weakness of the transmission system. In fact, the country's electricity production is heavily dependent on hydroelectric generation (~90% of the total installed capacity) strongly affected by seasonal variation of water inflows [3, 4].

The Lufubu Power Company is developing a two-staged 326 MW hydropower cascade on the Lufubu River in the Northern Province of Zambia (phase 1 with 163MW), with a 330kV transmission line. ZESCO will be the project's off-taker backed by an Implementation Agreement (IA) with Government.

Figure 1 – Lufubu Cascade project location

The Project is currently the most advanced base-load greenfield project under development in Zambia. The plant is expected to supply local demand and add grid stability. The Lufubu Cascade project finds ground on the planned strategy of the Zambian government, who is progressively carrying into effect the hydropower potential of the country, opening to IPPs and strengthening the transmission system on a vast scale looking at the neighbouring countries for energy exchange and trade purposes [2].

The study is intended as a technical assessment of the capability of the future Zambian electric grid to receive the power production of the Lufubu hydropower cascade in an electrical safe manner, as represented by its full-developed stage with about 326MW of capacity. In doing so, Studio Pietrangeli has prepared accurate models representing the Zambian power system, and has conducted an analysis to assess the adequacy of the planned network infrastructures, identifying the need for improvements to ensure safe operation of the new project within the rules of the regional electric code.

This study was conducted based on the generation and transmission data available at the beginning of 2015, considering a load demand scenario as per target year 2030, and tuned along with ZESCO's expansion plans.

In the target year 2030, the peak load demand forecast of Zambia is to increase from today (2015) 1,900MW up to 4,300MW and energy demand ~ 29,000GWh/y. In this scenario, Lufubu HPP will substantially contribute to cover the base load at its initial stage (plant factor 0.9) and peak hours load at its full development stage (p.f. 0.45), as well as reducing energy import. On the contrary, the vicinity of the project site to the 330kV Kasama – Mbeya corridor soon to be constructed provides a valuable, short path towards the Tanzanian boundary for power export purposes.

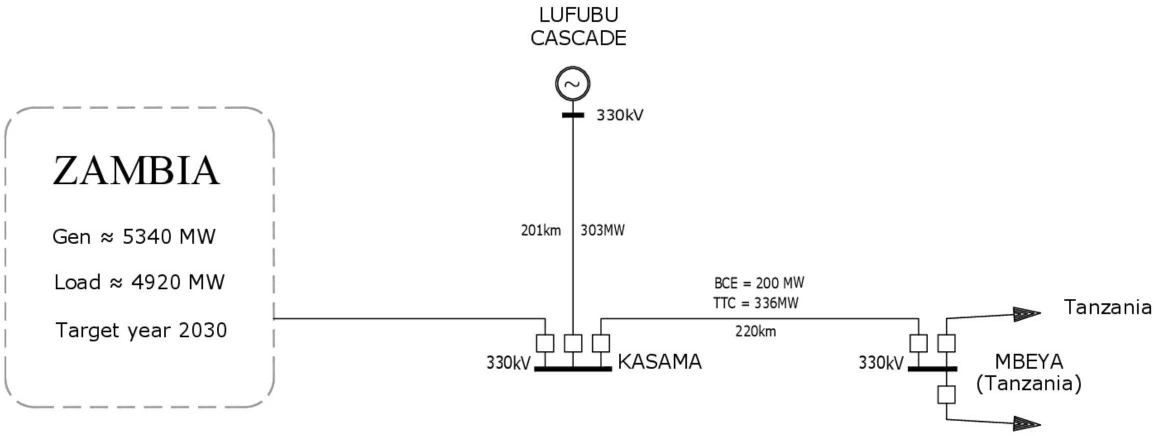

Figure 2 – Screenshot of a portion of the analyzed network topology (Lufubu HPPs Cascade) aimed to show the software interface and the developed model

II. Scope of the Study

The paper illustrates the methodology and results of the voltage collapse assessment performed on the Zambian power system, with the scope of highlighting potential criticalities of the Lufubu Cascade operation with the national grid, synchronously interconnected with the power systems of the neighbouring countries as DR Congo, Tanzania, Malawi, Mozambique, Namibia, Angola, Zimbabwe and within the SAPP. For this purpose, a complete model of the Zambian system for the target year 2030 was prepared, taking into account the inputs provided by the Client (LPC) and the national utility (ZESCO). The system is considered as a medium meshed interconnected system, due to several trans-boundary links, namely with Namibia, Botswana, Tanzania, Zimbabwe, Mozambique, South Africa, DR of Congo.

Multiple simulations were carried out to test the system and assess its stability limits. The study covers aspects such as security analysis, reactive compensation study, short-circuits assessment, (n-1) contingency, calculation and monitoring of overloads on international tie-lines, of possible regional voltage collapses. All the simulations performed revealed the weaknesses of the system and permitted us to conclude on how to extend its operation limits up to the desired level.

This paper focuses on the voltage stability assessment, with Lufubu Project at its full development stage.

For the purpose of the study, a computer software package was used, namely CYME PSAF (Power System Analysis Framework), making use of the load-flow and the voltage stability modules.

III. Zambian Power System

The Zambian electrical power system is operated under the aegis of the Southern African Power Pool (SAAP)/Southern African Development Community (SADC) as part of an interconnected power system, linking South Africa and Zimbabwe to the south via 330 kV lines, and the Democratic Republic of Congo (DRC) and Tanzania to the north and east at 220kV and 66kV voltage respectively.

In the north, the Lufubu Cascade will fill a geographical gap, providing a substantial input of about 330 MW to the grid, boosting by 13% the present 2,500MW installed capacity (95% hydro) targeting the planned 7,350MW in 2030.

As far as the transmission system is concerned, the 330kV system links the two major power stations of Kariba North Bank and Kafue Gorge. At the time of writing, the Extra High Voltage (EHV) system is composed of about 650km of 220kV lines and 3,700km of 330kV lines (existing and under construction), while 132kV and 88kV network in operation is interconnected mostly at regional level. The system is scarcely developed in the north of the country, so that the injection of the Lufubu HPPs Cascade power could represent a considerable boosting for the power system performances. The presented study is conceived to investigate it and support the economical viability of the needed investment.

IV. Lufubu Cascade Electric System

The three plants of the cascade will be linked to each other by 132kV overhead lines (OHLs) and from the terminal substation at Lufubu 1 a 330kV OHTL will interconnect the cascade with the national grid to 330 kV substation at Kasama.

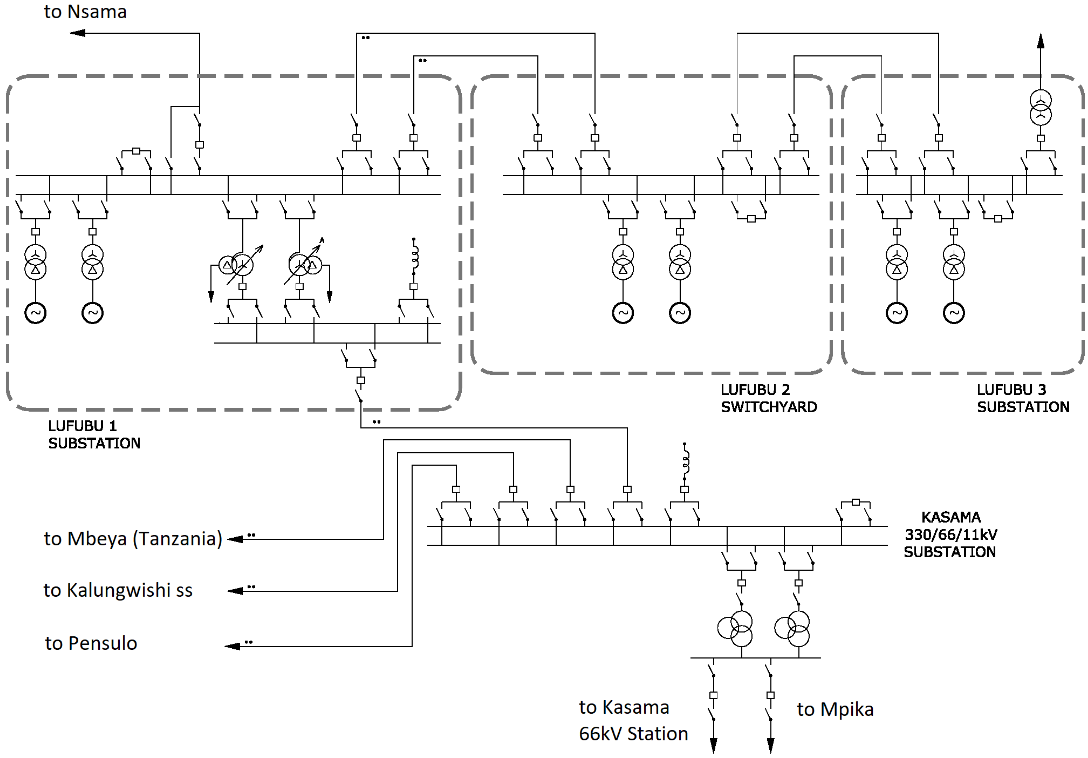

Figure 3 – Lufubu electric system single line diagram – Hydro Power Cascade high voltage connections scheme

The scheme includes (see figure above):

- two 132kV OHTLs from LU3 to LU2, as well the 132kV OHL to Nsama, single-circuit with ACSR (Aluminium Conductor Steel Reinforced) "Lynx", about 22 km long
- two 132kV OHTLs from LU2 to LU1, single circuit with twin bundle ACSR "Lynx", about 20.5 km long
- one 330kV single circuit OHTL linking LU1 to Kasama (201 km), rated 700MVA and equipped with twin bundle ACSR "Bison"; the design of this line has been recently reviewed tailoring its capacity to 400MVA, i.e. the maximum cascade output, for cost reduction purposes, terminating the line to the nearest Mporokoso substation (65km far).

This scheme will enable the full power capacity of the cascade to be transferred to the national grid via two 330/132kV autotransformers, as well as feeding the nearby Nsama district through a new 132kV substation. Lufubu Cascade will contribute to several ancillary services (e.g. black-start capability for system restoration in case of blackout event, P-f regulation, etc.) as required by established international operation regulations of vast synchronous power pools such as SAPP.

V. Transmission System Operating Scenarios

The design is based on – and takes advantage from – configurations already existing and applied in Zambia by the national utility, ZESCO. The following paragraphs gives evidence of the suitability of the proposed configuration.

Basic economic assumptions are made, such as 0.025 investment discount factor given for 50 years at 8% discount rate. The table below summarizes the main inputs of the Lufubu Cascade conceptual design, for both phases 1 and 2.

TABLE I. Lufubu HPP main design parameters

Phase	Lufubu HPP Installation and operation		
	Installed Power Capacity [MW]	***Plant Factor***	***Energy Production Cost [c$/kWh]***
1	163	0.9	4.8
2	326	0.45	5.5

Energy production cost associated with PHASE 2 reflects the increase of the installed capacity investment cost without major modification of the energy output, provided that the plant factor varies from 0.9 to 0.45.

The following paragraph depicts the transmission costs at 0.92 power factor for two representatives utilization factors (plant factor 0.9 and 0.45), calculated for the 330kV line of the project.

VI. 330kV Conductor Selection

According to ZESCO, it is common practice to equip the 330kV transmission lines with a twin bundle ACSR (Aluminum conductor steel reinforced) "Bison" conductor in the Zambian grid. Cross section and current density associated to this ACSR type have been checked out to ascertain if it fits the purpose of the Lufubu transmission requirements.

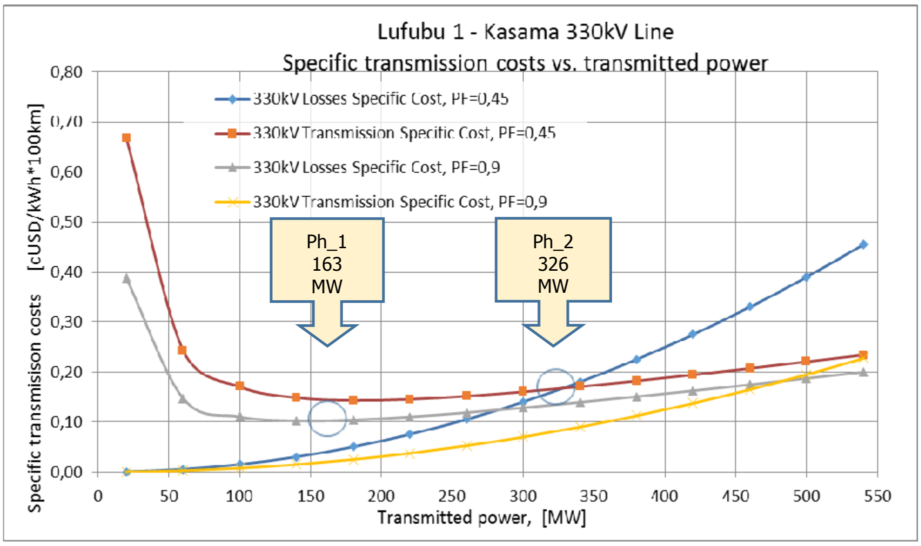

Figure 4 – 330kV 201km twin "Bison" ACSR line (LU1-KAS), specific transmission cost and V drop

The main features of the selected conductor are hereby recalled:

- ACSR "Bison", total cross section of 431.2 mm^2;
- aluminum cross section of 381.7 mm^2;
- ratio between aluminum and steel as 54x3.0/7x3.0=7.7;
- external diameter of 27 mm.

This conductor type and associated bundle configuration has been investigated to assess its suitability in respect to current density and specific transmission costs, on economic considerations in terms of minimum costs.

The following chart plots these costs (specific cost of losses, and total transmission costs) associated to the 330kV Lufubu – Kasama single circuit line equipped with the twin "Bison" line (specific costs given in cUSD/kWh*100km).

It is worthwhile noting that:

- in PHASE 1 (utilization factor 0.9 the line carries the selected power rating of 163MW at minimum cost of about 0.10cUSD/kWh*100km
- in PHASE 2 (utilization factor 0.45) the line carries the selected power rating of 326MW at minimum cost of about 0.17cUSD/kWh*100km

In conclusion, the selected conductor allows carrying the design power, in both scenarios, at minimum cost.

The resulting flat trend also permits a certain safety margin of the theoretical calculation in respect of those parameters whose determination is rather difficult, due to several uncertainties such as the actual cost of the produced energy, actual utilization factor of the line (hours per year operating at its full rating), unpredictable change of the rated current, etc.

In EHV (Extra High Voltage) transmission lines design, acceptable current density ranges from 0.7 to 1.6A/mm2 and above, depending on the afore mentioned parameters and from other operational considerations, the lower values owing to very long lines with high utilization factors.

The rated phase current of 647A, corresponding to 370MVA (i.e. 350MW @cosφ 0.92), is carried at 0.85 A/mm^2, which is found rather conservative.

Therefore, by considering:

- the uncertainty of the line operating assumptions
- neglecting the ACSR Steel section (i.e. 13% less in the total cross-section) in the carrying capacity of the conductor
- the conservative 0.92 power factor assumed

the results are deemed satisfactory in both operating phases.

VII. Voltage Stability Study Methodology

Whenever a disturbance – e.g. an increase in load – causes progressive and uncontrollable decline in voltage, the system enters a state of "voltage collapse". This state is associated with saddle node bifurcation and reactive power limitations of the power system.

Voltage stability assessment aims at verifying the capability of the interconnected system to maintain steady acceptable voltage profile at load buses under normal and contingency conditions, and any margin against the incipient entering into this state.

The main factor affecting this phenomenon is the inability of the system in achieving reactive power balance which generators, transformers tap-changers operation, load recovery dynamics concur to.

Voltage drop is also followed by increased current and reactive power consumption by lines and transformers inductance, reduced reactive supply by compensating capacitor banks and lines capacitance. After generators short-time overexcitation (seconds to minutes), the AVRs reduce its field current within tolerable limits, and hence the reactive power supplied to the grid, therefore that portion of the grid undergoes voltage collapse and could be consequently tripped by undervoltage and overcurrent protection relays.

The aim of this part of the study was then to assess the collapse risk, which may occur in a specific area of the grid, say the nearest 330kV load bus to the Lufubu Cascade. The bus is identified in the 330kV Kasama station, along the corridor towards Tanzania, ~200km from the border. The assessment investigates the event whenever, in presence of increasing power export across the Kasama bus, the synchronous generators of that area (e.g. Lufubu HPPs units) reach upper limits of reactive power continuous supply in overexcited condition and, therefore, cannot support the bus voltage profile.

The assessment has been done applying the criterion of the variation of the reactive power generation as the load active/reactive demand varies, for a specific network area affected by Lufubu power transfer. This simple criterion is particularly suitable if implemented by a load flow program to analyse a multi-node system, such as the one composed by the subject network [5, 9, 12]. The application of a static stability criterion is widely justified in literature [8, 11, 12], i.e. how static power system models can be used to compute the loading margin to voltage collapse due to fold or saddle node and its sensitivities to parameters and controls. The static models are understood to have underlying dynamics, responsible for the dynamic voltage collapse because of the so-called fold bifurcation.

For the purpose of the study, a "Voltage Collapse Proximity Indicator" (VCPI), derived from the above criterion, is hereby referred to in the analysis, carried out by running several AC load flow simulations [8, 9, 10]. The definition of the index at the ith node (bus) is:

$$VCPI = \frac{\sum \Delta Q_{gen}}{\sum \Delta Q_{bus\ load}}$$

where:

$\sum \Delta Q_{gen}$ is the sum of all the generated reactive power increments;

$\sum \Delta Q_{bus\ load}$ is the sum of the increments of the reactive load demand at the examined node (i.e. Mbeya).

It is worthwhile recalling that when the system approaches the critical state the index tends to infinity. The non-convergence of the Newton-Raphson method is retained as the identification of the critical state condition, i.e., there is no more equilibrium beyond this point between reactive demand and generation and the network is no longer within a steady-state voltage stability area.

Extreme measures can be implemented after a disturbance to bring the system from emergency to normal state, prior to falling into collapse state, with impact on customers [6, 7]:

- automatic blocking of the distribution transformers OLTCs;
- load shedding initiated by under-frequency protection relays.

The scope of the study was to assess a security margin, a measure of the above defined proximity to a loadability limit, by stressing the system along the specified direction of load increase. In doing this, the Q margin was thereby assessed as the distance to a particular loadability limit, obtained by varying the active and reactive power injection at a single bus.

The multiple load flow solutions allows construction of a PV curve (bus voltage vs. increasing power), showing a "nose" – the sought limit, which is the ultimate operating point corresponding to the incipient instability, beyond which it is no longer possible to achieve power flow solutions.

VIII. Discussion of Results

The analysis covered the area of interest in the north-eastern part of the country, where the Lufubu power output is likely to be wheeled towards Tanzania, across the shortest available corridor – through Mbeya – thus minimizing transmission losses. As mentioned before, a *power flow-based* analysis has been adopted, by increasing the power export towards Mbeya up to an amount to identify its feasible maximum, wherein allowed to run power flow iterations.

The load at the end of the corridor area (Mbeya) was increased in variable steps progressively to a level where there was system collapse.

In this analysis, the PQ load increase at Mbeya bus is accompanied by the action of the OLTC of the Lufubu autotransformer, which operates trying to keep the sending end bus as high as possible.

Acceptable VCPI (~≤2) are gained up to 320÷350MW of power export (step 5-6). The Kasama – Mbeya sub-system enters in an unstable behavior where VCPI start increasing to infinity and V_{mbey} falls down to 0.8p.u.

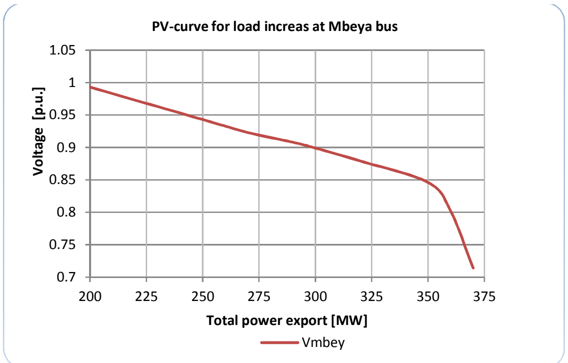

Figure 5 – VP-curve for stability margin assessment at Mbeya

The loadability limit is identified as somewhat close to 360MW, hence 180% of the initially planned export (200MW), where the "nose" shown by the curve is exhibited and beyond which no further stable operating points can be found. System operation in the high slope stretch of the VP-curve must be avoided.

The next graph shows the VCPI plotted with VQ-curve at each bus, together with the "global" one relevant to the overall system. As can be seen, the operation of the OLTC at Lufubu temporarily attempts to improve the voltage, by increasing V_{luf}. The last graph shows VQ-curve at Kasama bus.

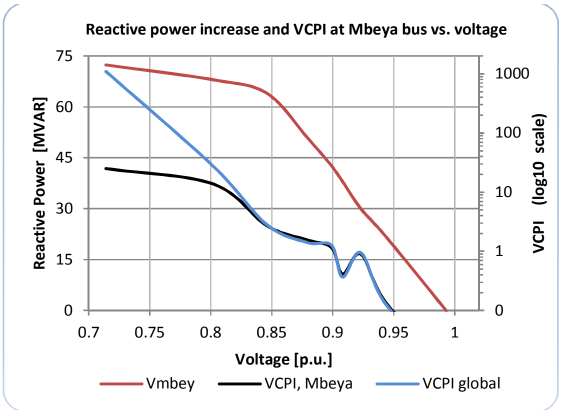

Figure 6 – VQ-curve at Mbeya with global VCPI

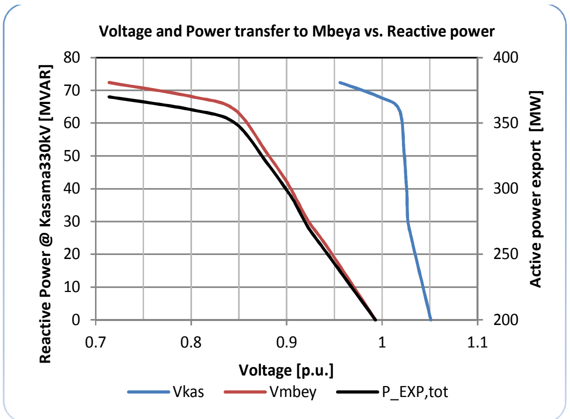

Figure 7 – VQ-curve at Kasama with active power export

CONCLUSIONS

In the framework of the transmission system engineering relevant to the Lufubu hydropower cascade interconnection to the Zambian national grid, the consultant has focused the network stability studies on the robustness of the grid against voltage stability behaviour. Voltage stability investigation finds acceptable operation up to ~350MW of export to Mbeya bus (Tanzania). In fact, VCPI ~≤2 is obtained up to 320÷350MW of power export, while the Kasama – Mbeya sub-system enters in an unstable behavior suddenly after, wherein VCPI start increasing to infinity and V_{mbey} falls down to 0.8p.u. The loadability limit is identified in about 360MW, hence 180% of the initially planned export (200MW at Mbeya bus).

The study has shown that, even conservatively ignoring boundary countries participation to voltage regulation, the calculation of the stability margin is notably valuable if both the extension of the grid (spanning more than 2000km) and the exiguous generation park in the vicinity of the node of interest, which is more than 1000km far from the electric center of the national grid (approx. in Lusaka), are considered.

For sakes of record, as per today there are two interconnecting projects at advanced stage of implementation, namely the Kasama – Mbeya line to Tanzania and the Pensulo – Chipata – Songo to Mozambique.

In conclusion, the coming on line of the Lufubu Cascade provides a valuable power input into the ZESCO grid, readily available not only for supporting the internal demand concentrated in the middle of the country, but also for export through the nearby corridor to Tanzania, avoiding power transfer from other far plants, and promoting trading among the neighbouring countries. Among the main benefits, to highlight:

- strengthening and improvement of north-eastern generation and power transfer capacity
- improvement of grid voltage regulation, due to an additional dispatching point in Kasama; therefore, system control and reliability is significantly improved
- strategic features in case of re-energization of the entire electric grid from an additional resource, during black-outs

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