

Voltage collapse assessment of the Lufubu – Kasama 330kV planned overhead line and power transfer capacity on the Zambia – Tanzania cross-border corridor

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SUMMARY

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) and transaction advisors Fieldstone South Africa, is developing the design, environmental and social impact assessments (ESIA), obtaining concessions and licences, and negotiating with other interested parties (off-takers, civil works contractors, operation and maintenance contractors, etc.). Moreover, LPC is currently in negotiations with the Zambian government for the Implementation Agreement (IA) and with national electricity utility, ZESCO, for the Power Purchase Agreement (PPA).

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).

The paper provides an illustration of the general background of Zambia's electrical system and the selected electrical scheme for the evacuation of the Lufubu Project power output, as well as the planning criteria, methodology of the voltage collapse assessment. Voltage collapse prediction analysis is described, and stability assessment results reported.

Finally, total transfer capacity (TTC) evaluation is also illustrated.

KEYWORDS

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

1. 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 [4, 5].

The Lufubu Power Company is developing a 163 MW hydropower cascade on the Lufubu River in the Northern Province of Zambia. ZESCO will be the project's off-taker backed by an Implementation Agreement (IA) with Government. The first phase of the project will see the construction of a cascade of three hydropower plants on the Lufubu River with an aggregate installed capacity of 163MW along with a 330kV transmission line ("Phase 1"). The second phase of the project will see a doubling of the aggregate installed capacity to 326MW ("Phase 2").

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 exploitation of a new energy source, whatever its nature, through the development of an integrated system, is based on needs to be validated by the most suitable means. In the case of power systems, the study of the network behaviour by performing a technical analysis with the so-called "network study" represents the instrument and methodology applied worldwide in the last decades. 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. A unit commitment schedule was proposed and agreed with LPC for each analysed scenario, based on an economic merit order ranking – say, the cheaper plants in terms of specific generation cost come first, wherein Lufubu Cascade is ranked 8th out of more than fifteen plants.

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 0.85) 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.

2. 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.

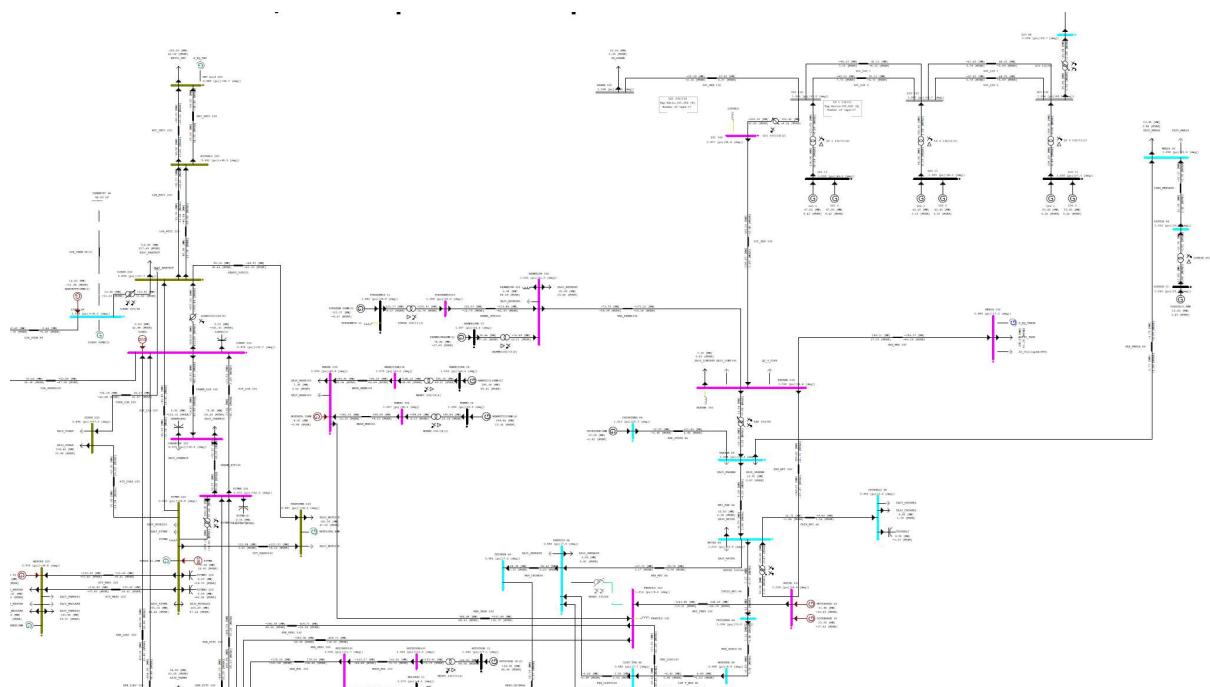


Fig.1 – Screenshot of a portion of the network topology of the area of interest (north-eastern part of Zambia, boundary with Tanzania); up right the 3 HPPs of the Lufubu Cascade system.

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.

3. 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. The figure shows the present transmission grid as per year 2015, including planned and committed transmission/generation projects at time horizon 2019.

The Zambian electricity supply industry consists of three major market players, namely ZESCO (Zambia Electricity Supply Corporation Limited), CEC (Copperbelt Energy Corp.) and the LHPC involved in generation, transmission, distribution and supply. System operation is coordinated by ZESCO's national control centre in conjunction with the various subsidiary control centres.

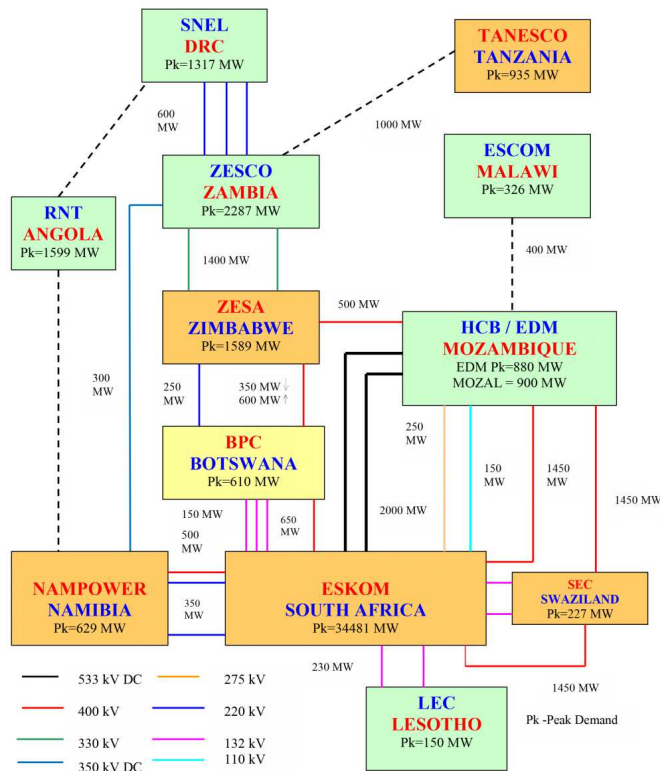


Fig.2 – Interconnected countries in SAPP with relevant exchange capacity (source: SAPP website)

The mining sector and domestic consumers account for 82% of total electricity consumption. Zambia is also faced with the challenge of satisfying the demand of more than 80% of its population with renewable forms of energy. Presently, the system is operated with heavy load shedding schedules due to insufficient generating capability to cover the increasing load demand, as per the expected growth in the next few years between 150 to 200 MW per annum, with a severe and immediate shortfall in supply. Therefore, both increasing the country's electricity generating capacity and reinforcing the transmission infrastructures are priorities for fulfilling the short and medium term energy needs, as several projects are planned, mostly in the south (medium and large hydropower plants such as Itzhi Tezhi recently commissioned, and Batoka Gorge, Kafue Gorge Lower as well as thermal plants such as Maamba, a newly connected plant).

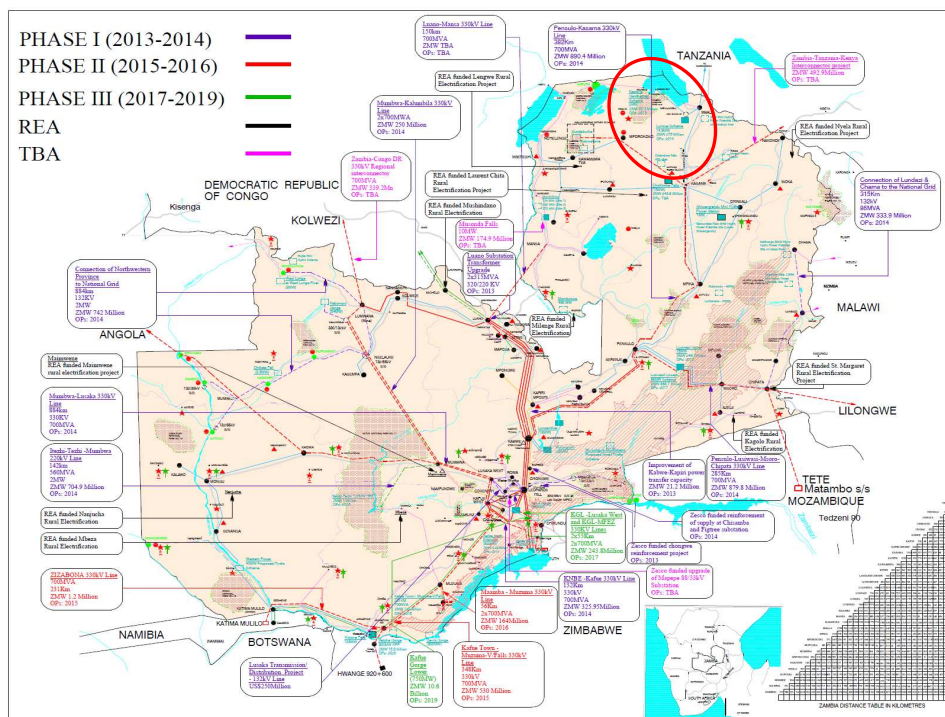


Fig.3 – Zambian grid including planned and committed transmission/generation projects as per year 2019 (source: ZESCO)

In the north, the Lufubu Cascade (as marked by the red circle in the figure above) 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.



Fig. 4 – Pensulo – Kasama 330kV line approaching Kasama station, Zambia, 2017

4. 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.

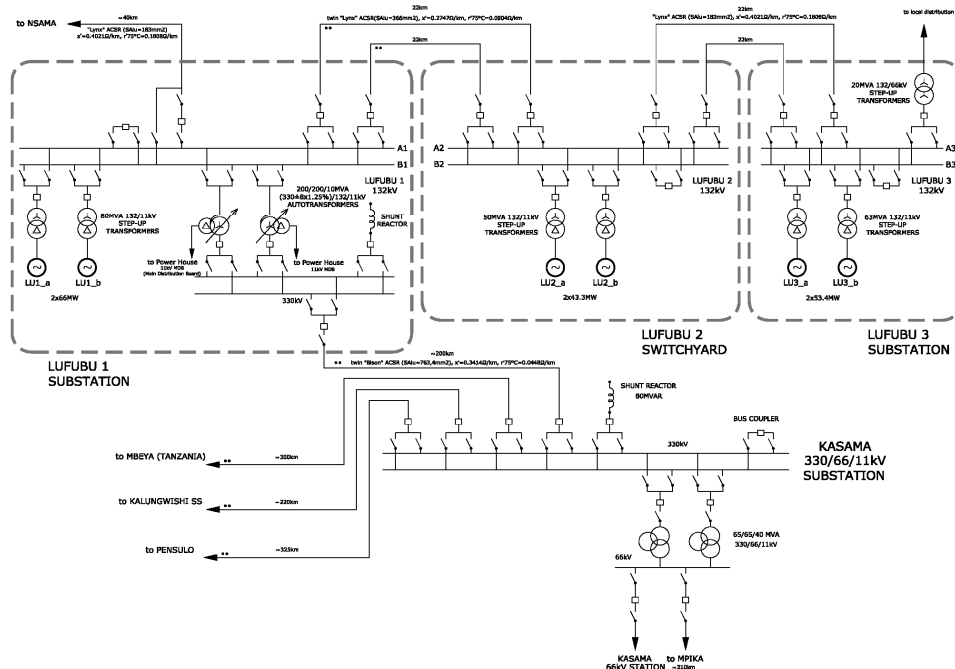


Fig.5 – Lufubu electric system single line diagram

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 by tailoring its capacity to 400MVA, i.e. the maximum cascade output, for cost reduction purposes, terminating the line to the nearest Mporokoso substation.

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.

5. GENERAL PLANNING CRITERIA

Transmission system security is based on conventional deterministic criteria that assure, on the basis of experience, a high continuity of supply of loads at the EHV and HV levels, as well as security of evacuation of power from the power plants. As a rule, it has been assumed in the load flow studies, that all the generators should be operated, at peak system demand, with a reactive power overexcited margin of at least 15%, in normal conditions with all the lines in service, and of at least 10 % in emergency contingency condition.

For the hydroelectric generating units the underexcited operation is accepted in all the power plants. The assumed MVAR absorption capacity has been obtained from the manufacturer's P-Q capability curves, by deducting a 15% margin for security of operation.

Line shunt compensation is planned with the following main aims:

- to enable no-load energization of the lines in any system operation condition from Lufubu HPP to Kasama station;
- to enable sub-system operation interested by minimum power transfer on lines;
- to prevent an excessive underexcited operation of generators;
- to assist in system voltage control within the range $\pm 5\%$ about average value at EHV level

A voltage regulation task has been carried out for balancing reactive power exchange across the network, prior to proceeding with power flow analysis. Wherever needed, ZESCO reinforcement plans have been supplemented by additional equipment (lines, transformers, shunt reactors, capacitor banks) to achieve sound voltage profiles.

Finally, load characteristics may have an important influence on system voltage stability as power system stable operation depends on the ability to match continuously the electrical output of generating units to the electrical load. The complexity of load modelling is mainly due to uncertainty in composition of mix estimation, but indeed there is the need for models that are sufficiently simple and realistic at the same time.

A static load model expresses the characteristics of the load at any instant as an algebraic function of the bus voltage rms value and frequency at that instant. On a more general basis, the relationship between power and voltage can be expressed by the exponential model:

$$P = P_0(V/V_0)^a \quad Q = Q_0(V/V_0)^b$$

where P_0 and Q_0 are the active and reactive power respectively when the bus voltage is at its nominal or reference value, V_0 . Exponent ‘a’ usually ranges between 0.5 and 1.8, while ‘b’ may range from 1.5 to 6, and is also representative of the dependence on magnetic saturation in distribution transformers and motors and so it varies non-linearly with voltage, so that, at higher voltages, Q tends to increase significantly [16]. The model adopted in this study is of the exponential type, with coefficients which have been assumed as per previous ZESCO’ studies, respectively:

- about 2000MW (out of 4942MW) in the Copperbelt zone represented with $a=0.8$, $b=4$
- the remaining load (i.e. about 2300MW) represented with $a=1$, $b=3.3$

Load export is represented as constant power ($a=b=0$), except for Namibia ($a=b=2$), at constant impedance.

The extensive load flow and voltage regulation analysis performed tailored to the voltage stability assessment shows that the infrastructures planned at the target year allow the forecasted internal peak demand to be covered providing a reserve margin sufficient to allocate more than 600MW for export purposes, as it has been considered in the scenarios of this study.

6. 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 meeting 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.

As mentioned, the voltage collapse risk has been evaluated for a specific network area affected by Lufubu power transfer. The assessment has been done applying the criterion of the variation of the reactive power generation as the load active/reactive demand varies. 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 [11, 15, 18]. The application of a static stability criterion is widely justified in literature [14, 17, 18], 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. By computing load power margins and their sensitivities with static power system equations, it has been demonstrated that the results are accurate for a general and sensible class of underlying dynamic representation of the phenomenon, thus enabling commercial software to evaluate and provide indication about voltage collapse blackouts and related proximity.

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 load flow simulations in AC [14, 15, 16]. The definition of the index at the i^{th} 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.

Once the instability risk is identified, preventive measures will have to be adopted such as:

- power factor (p.f.) improvement;
- identification and availability of those generating units with reactive power margins;
- setting the transmission buses affected by heavy power flows at the highest operating voltage.

Extreme measures can be implemented after a disturbance to bring the system from emergency to normal state, prior to falling into collapse state, with evident impact on customers [12, 13]:

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

A common practice is to assess the system ability to survive credible contingencies with the sole help of controls which have no impact on customers. Complementary to this, the adequacy of stronger controls is checked against more severe disturbances not covered under usual security criteria [11, 12, 18].

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 analysis was applied to a weak area identified as the corridor to Tanzania, which is considered to be most prone to voltage instability, by increasing the lumped load at Mbeya 330kV bus from the forecasted 200MW of the target year up to a maximum allowable by the system at constant power factor.

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.

7. 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 following table illustrates the results of the analysis with numerical outputs. It includes, per each step of simulation, Lufubu generators V and Q variation (and 330kV autotransformer tap changer position) vs. exported load increase towards Tanzania (Mbeya), with V p.u. at Kasama and Mbeya buses. Local and global VCPI values are also reported. The load at the end of the corridor area (Mbeya) was increased in variable steps progressively to a level where there was system collapse.

step	GEN TOT		LOAD TOT		Global p.f.	Lufubu							Kasama	Mbeya						
	Ptot	Qtot	Ptot	Qtot		cos fi	Vluf	TAP AutoTR 330/132	Vlu1_2 11kV	Vlu2_11 kV	Vlu3_11 kV	$\Delta Q_{gen,j}$ uf		Plu1_kas	Vkas	Vmbey	ΔP_{exp}	ΔQ_{exp}	P_EXP,tot	VCPI _{LUF}
#	MW	MVAR	MW	MVAR		p.u.	%	kV	kV	kV	MVAR	MW	p.u.	p.u.	MW	MVAR	MW			
0	5340.0	1160.7	4920.0	866.9	0.985	1.071	101	11.6	11.6	11.5	37	297.3	1.051	0.993	0	0	200	0	0	0
1	5390.7	1163.8	4975.7	890.4	0.984	1.061	102	11.6	11.6	11.5	12	297.2	1.033	0.943	50	22	250	0.5	0.1	0.1
2	5409.4	1171	4995.0	898	0.984	1.063	103	11.6	11.6	11.5	29	297.2	1.027	0.923	70	30	270	1.0	0.9	0.9
3	5430.6	1174.3	5017.0	907	0.984	1.072	104	11.6	11.7	11.8	45	297.2	1.026	0.908	90	38	290	1.2	0.4	0.4
4	5440.0	1179.6	5026.6	911.2	0.984	1.076	105	11.6	11.7	11.8	55	297.1	1.025	0.899	100	43	300	1.3	1.3	1.2
5	5462.0	1192.7	5048.3	920.5	0.984	1.086	105	11.9	11.9	11.9	75	296.9	1.023	0.879	120	51	320	1.5	1.4	1.6
6	5494.5	1227.8	5078.8	933	0.984	1.103	106	12.0	12.0	12.0	116	296.2	1.018	0.846	150	64	350	1.8	2.8	2.7
7	5507.0	1282.6	5087.5	935	0.984	1.091	106	11.9	12.0	12.0	134	295.6	0.997	0.802	160	68	360	2.0	27.4	13.7
8	5523.0	1392.2	5094.6	935.1	0.984	1.064	106	11.9	12.0	12.0	165	294.5	0.956	0.714	170	72	370	2.3	1096.0	25.1

Table 1 – Set of input and output data of the multiple power flows run for the voltage stability margin

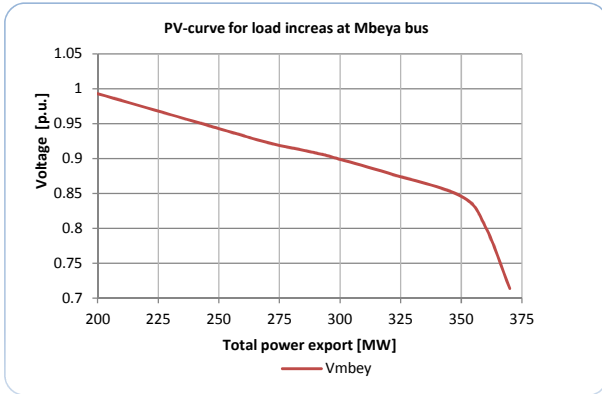


Fig 6 – VP-curve for stability margin assessment at Mbeya

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 subsystem enters in an unstable behavior at step 7, wherein VCPI start increasing to infinity and V_{mbey} falls down to 0.8p.u. The loadability limit is identified as somewhat close to 360MW, hence 180% of the initially planned export (200MW). The “nose” shown by the curve corresponds to step 8, 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 (left side) 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 graph on the right shows VQ-curve at Kasama bus.

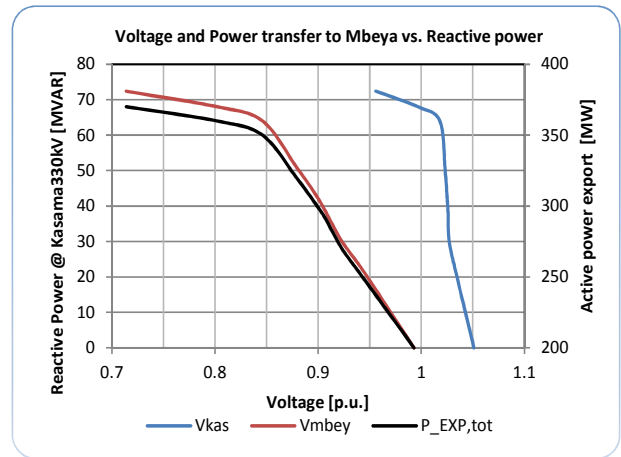
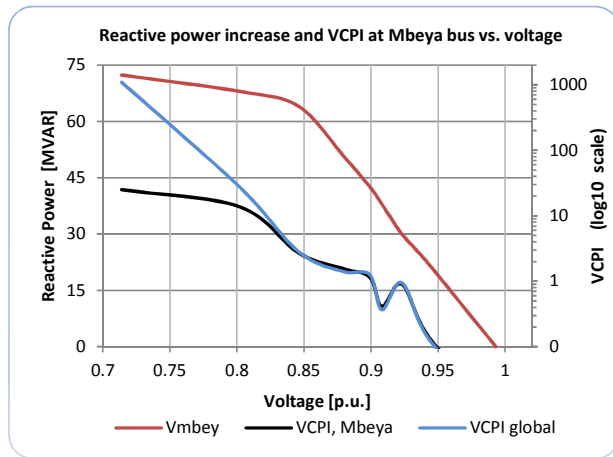


Fig 7 and 8 – VQ-curve at Mbeya with global VCPI (left) and at Kasama with active power export (right)

8. TOTAL TRANSFER CAPACITY EVALUATION

An additional result of the analysis was the maximum transfer capacity assessment towards Tanzania, without any further compensating measure.

Transmission System Operators provide procedures on how to assess transfer capacities between countries [19]. The maximum amount of power that can be transferred across the borders of two neighboring countries – without violating any security criterion – is called the Total Transfer Capacity (TTC). A security margin is properly introduced in practice to account for uncertain conditions and input data mismatching, thus resulting in the Net Transfer Capacity (NTC).

It is generally accepted that the maximum transfer capacity assessment is mainly carried out with respect to thermal capacity of the interconnections against maximum power flow. Indeed, the main issue with which this task has been undertaken under the present study is the voltage stability. The common set of programs of cross-border transactions and the net balances of each TSO area at the target year considered is the one supposed for, represented by the base case (BCE) of 624MW.

Starting from the BCE, the power flow can be increased by an extra amount (over the base case) ΔE that can be exchanged continuously from one country to another while ensuring the safe operation of both interconnected systems. This amount has been taken in correspondence with the first occurrence of any bus operating voltage falling down to 0.85 p.u. In this regard, it is worthwhile mentioning that this threshold is much slacker with respect to what is recommended in SAPP [6], i.e. the so-called maximum power transfer as determined when “*any busbar voltage drops below 0.95 p.u. for system healthy conditions, unless agreed between utilities*”. On the other hand, the condition “*power flow on the corridor exceeds 95% of the maximum power transferred at the knee point of the PV curve for that corridor (P_{max})*” is met.

The margin ΔE , added to the initial transaction value BCE taken in account between the concerned countries or zones, gives the total transfer capacity (TTC) between these countries:

$$TTC = BCE + \Delta E$$

The (n-1) contingency prescribed by some regional regulations (SAPP, ENTSO-E, etc., [20]) could be fulfilled only if the regional plans account for doubling the line of the export corridor towards Tanzania (i.e. the Kasama – Mbeya line).

The analysis has been performed by means of the CYME PSAF voltage stability module, with the aforementioned *continuation power flow* method, which finds a continuum of power flow solutions using a given load direction change. Three scenarios have been investigated. The first one, addressed in the previous paragraph, deals with P,Q variation at Mbeya bus. The other two deal with an increase of all the cross-boundary export power and the overall load demand of the network.

The attention given to the Mbeya bus is dictated by its vicinity to the nearest dispatching point of Lufubu, as the Kasama – Mbeya line is the nearest and shortest cross-border corridor.

It is evident from the results, illustrated in the following paragraphs, how the transfer limits are not dictated by the lines’ thermal limits at all (still very far on the 330kV interconnecting lines), the voltage stability being the main issue.

TTC VS. EXPORT INCREASE

Freezing the intervention of the transformers OLTCs, the analysis was run in two different modes: i) load increasing at constant p.f., and ii) load increasing by active power only (p.f. increasing accordingly). The increase of loads covers the export to boundaries only.

In case i), the assessed voltage stability limit is 32%. It means that the system is able to supply a power export increase up to 32% (i.e. +202MW, totaling 826MW), equally distributed on the boundary buses, up to the collapse of any bus as this happens at Mbeya (0.75 p.u.). The voltage stability margin applied for the TTC computation is the value corresponding to the operating voltage of any bus not below 0.85 p.u. In this case, as Mbeya bus exhibits 0.85 p.u. with 760MW power flow, the adopted margin is 22% (136MW) and therefore the computed transfer capacity ($TTC = BCE + \Delta E = 624 + 136$) is 760MW.

In case ii), the limit evidently increases to 81% (+506MW, totaling 1130MW) due to the improved p.f. Mbeya bus is affected by collapse down to 0.78 p.u. Therefore, the adopted margin is 75% (466MW), and the computed transfer capacity (TTC = BCE + ΔE = 624 + 466) is 1090MW.

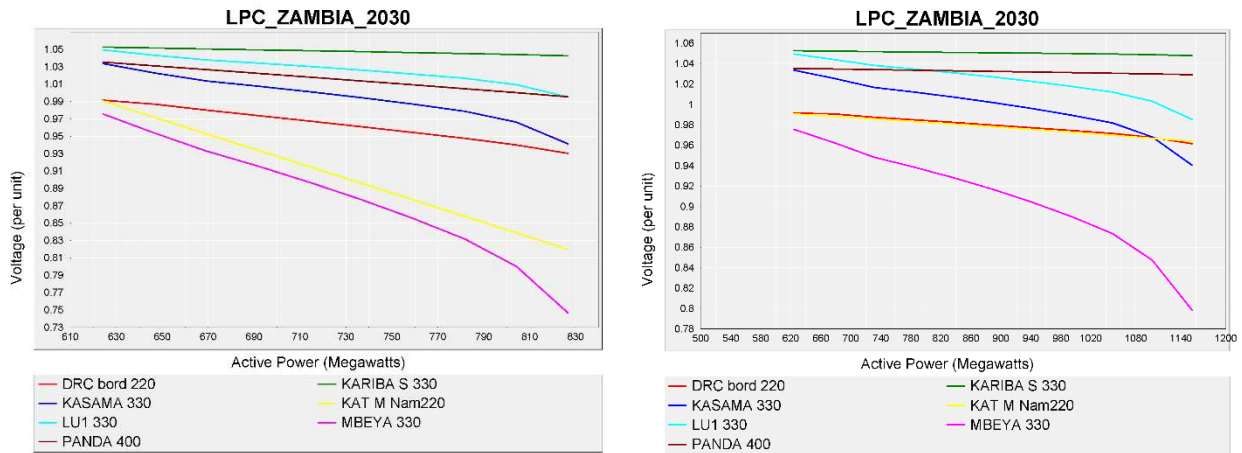


Fig 9 and 10 – Voltage at 330kV buses of boundary interconnection in case i) (left), and ii) (right)

TTC vs. OVERALL LOAD DEMAND INCREASE

The last task deals with a step increase of active power equally distributed on the overall load demand (export included). The analysis was performed by freezing the intervention of the transformers OLTCs, with load increasing by active power only (p.f. increasing accordingly). The voltage margin limit was assessed at 7.2%, i.e. the system is capable to operate within constraints up to an increase of +356MW of the load demand, thus totaling about 5298MW.

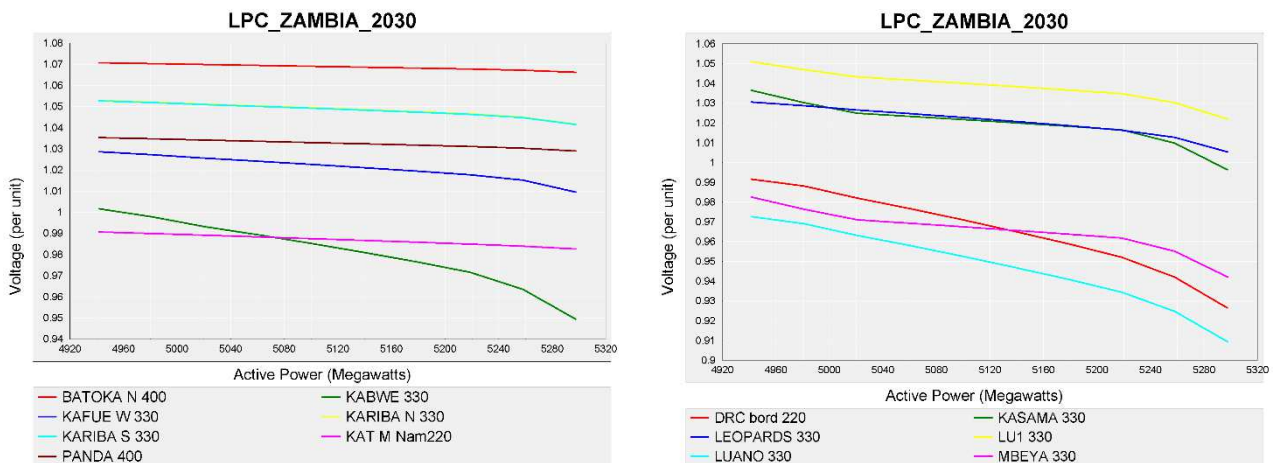


Fig 11 and 12 – Voltage at 330kV buses of the network, south and centre zones (left), centre to north-eastern (right)

The monitored voltage buses, shown in the charts, still maintain healthy voltage profiles.

9. CONCLUSIONS

The paper outlines the need to consider, at the planning stage of transmission systems, some of the major issues troubling TSO, i.e. achieving both maximum power transfer capability and optimal voltage stability margin, not to mention how this matter deals also with procurement, installation, operation and maintenance of the equipment pertaining to the transmission grid.

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 collapse behaviour. The main findings of the study are as follows:

- The load flow analysis shows that the infrastructures planned in the target year allow covering the forecasted internal peak demand providing reserve margin (against peak load) sufficient to allocate more than 600MW for export purposes
- The majority of the internal main corridors are operated within their thermal limits with adequate margins. The south-to-north backbone from Batoka, Kariba and Kafue HPPs transfers about 3800MW (76% of the entire load demand) with the higher loading around 80%, peaking on the Muzuma – Kafue lines (88%), in the investigated scenario. On the contrary, the western links to Angola and Namibia are underloaded.
- Voltage stability investigation finds acceptable operation up to ~350MW of export to Mbeya bus (Tanzania). In fact, VCPI $\sim \leq 2$ 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_{mbeya} 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 assessed total transfer capacity (TTC) to boundary interconnections is approx. 760MW, without any additional reactive compensation measure, with a margin of 22% against the export program, while TTC increases up to 1090MW by adopting p.f. correction, with a widely higher margin.
- The assessed TTC to the overall network (internal load buses and export), with load increasing by active power only (p.f. increasing accordingly), results in a voltage margin limit at 7.2%, i.e. the system is capable to operate within constraints up to an increase of +356MW of the load demand (up to 5298MW).

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.

In addition to that, despite further improvement, it is believed that the assessed total transfer capability is realistically conservative and underline the foundation of the power exchange framework presently progressing with Tanzania between ZESCO and TANESCO.

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 this regards, it is worthwhile mentioning that, real-time monitoring means of voltage criticalities are currently available and of easy implementation, in particular, worthy for the case studied:

- identification of areas/sub-regions/buses in Zambian power systems prone to voltage instability under particular operating conditions and contingencies; this is indeed recognized as true in the north-eastern region, where the Lufubu interconnection will be realized, due to the lack of regulating generating stations and the length of the 330kV point-to-point lines without intermediate stations
- determination of reactive power reserve requirements to ensure secure system operation
- determination of a set of contingencies that spans the range of credible failure events
- performance of typical on-line steady state (n-1) contingency scenarios in the identified areas
- coordination with SAPP and boundary dispatching/TSO centers to ensure efficient and rapid corrective measures in case of incipient instability

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

It is also worth to mention the role of the project also in meeting the local communities load demand (the Lufubu site neighbouring areas), achieved by sustainable green energy production (hydropower).

BIBLIOGRAPHY

- [1] “Lufubu Hydroelectric Project Transmission System Feasibility Study Report”, Studio Ing. G. Pietrangeli, 2015
- [2] “Scoping Mission Report, Zambia”, Africa-EU Renewable Energy Cooperation Programme, EUEI Energy for Development Partnership Dialogue Facility, August 2016
- [3] “The Electricity (Grid Code) Regulations, 2013”, Government of Zambia, Aug 2013
- [4] “Zambia nation-wide power blackout of June 4, 2006”, Report by the expert team constituted to investigate the power outage, Energy Regulation Board, July 2006, Lusaka, Zambia
- [5] “Nation-wide blackouts of 19th, 21st and 22nd January 2008”, Report of the Committee, Energy Regulation Board, March 2008, Lusaka, Zambia
- [6] “Transmission planning criteria”, Southern Africa Power Pool, SAPP-SADC, January 2012
- [7] “Zambia Energy Sector Profile”, Zambia Development Agency, 2014”
- [8] M. Larsson, C. Rehtanz, J. Bertsch, “Monitoring and operation of transmission corridors” (IEEE Bologna PowerTech Conference, 2003, Italy)
- [9] Working Group SC 22-12 CIGRE. “The thermal behaviour of overhead conductors – Section 1 and 2: Mathematical model for evaluation of conductor temperature in the steady state and the application thereof” (Electra number 144 October 1992 pages 107-125)
- [10] “Definition And Classification Of Power System Stability”, IEEE/CIGRE Joint Task Force, June 2003
- [11] “Modelling Of Voltage Collapse Including Dynamic Phenoma”, CIGRE Task Force 38.02.10 of Study Committee 38 (Power System Analysis and techniques), 2000
- [12] “Criteria And Countermeasures For Voltage Collapse”, CIGRE Task Force 38.02.12, October 1995
- [13] “Voltage Collapse Mitigation”, IEEE Power System Relaying Committee, WG K12, December 1996
- [14] “Impianti Elettrici”, F. Iliceto, Pàtron, Bologna 1981
- [15] “Power System Stability and Control”, P. Kundur, McGraw-Hill, New York, 1994
- [16] “Behaviour of loads during voltage dips encountered in stability studies. Field and laboratory tests”, F. Iliceto, A. Ceyhan, G. Ruckstuhl, IEEE Transactions on Power Apparatus and Systems., Vol. PAS-91, n°6, 1972
- [17] “The irrelevance of electric power system dynamic for the loading margin to voltage collapse and its sensitivities”, I. Dobson, NOLTA, IEICE, July 2011
- [18] “Voltage stability indicator at the proximity of the voltage collapse point and its implication on margin”, G. Singh Deol, S. Sao, H. Singh, V. Gupta, Asian Journal of Computer Science and Information Technology, 2011
- [19] “Definitions of Transfer Capacities in Liberalized Electricity Markets”, Organization of European Transmission System Operators (ETSO), April 2001
- [20] “Procedures for cross-border transmission capacity assessment”, ETSO, October 2001