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Engineering of Power Flow Control across the Zambia – Zimbabwe Interconnector with Phase-Shifting Transformers

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***Abstract* — The paper reports the engineering performance evaluation and simulation studies of the phase-shifting transformers (PSTs) applied to the planned interconnector between the national electric grids of Zambia and Zimbabwe, in Africa. This solution was proposed to the Zambezi River Authority, the implementing agent for the Batoka Gorge Hydroelectric Scheme (BGHES), on the Zambezi River, for addressing the issue of controlling power flows across the newly conceived interconnector in a reliable, safe and resilient manner. For the engineering purpose, the feasibility studies have proved and confirmed the expected performances and effectiveness on the controlled interconnector operation. The authors describe the assessment of the viability of this solution from a system operation perspective, having carried out a screening of possible alternatives other than PST-based, and checked the expected PST's capabilities in both static (load flow) and dynamic behaviour through a comprehensive network study campaign.**

***Keywords*—power corridor, phase-shifting transformer, transient stability, power flow control, FACTS**

I. INTRODUCTION

The Batoka Gorge Hydroelectric Scheme (BGHES) has been demonstrated to be the least-cost of a series of hydropower investments originally conceived in the '70s as part of a cascade on the Zambezi River Basin, shown in figure 1. The project is being implemented by the Zambezi River Authority (ZRA), an organization equitably owned by the governments of Zambia and Zimbabwe, to develop, operate, monitor and maintain hydropower projects along the Zambezi River common to the two Southern African countries [1]. The power sector of both countries has been struggling with the challenge of supplying reliable electricity to meet the needs of the growing economies and providing universal access to electricity. In this scenario, the hydropower resources of the Zambezi River Basin, with more than 5,000MW already implemented (with Cahora Bassa, Kariba and Kafue Gorge dams) and about 15,000MW of potential, are integral to the development of the power sector in Zambia and Zimbabwe.

As part of the scheme, the project includes two hydropower plants, one per each riverbank, totalling 2,400MW (10,200GWh/y of energy production) with relevant stepping-up substations interconnected via 330kV circuits, and several lines heading to the respective national grids. The rated power of each power plant will be evacuated respectively via 330kV overhead lines (OHLs) towards Zambia, 400kV to Zimbabwe.

The project's extent had to be supported by a suitable power evacuation scheme, capable to operate in the most stringent contingencies also in consideration of the role of the BGHES within the regional generation park.

Fig. 1. BGHES project location

II. STUDY'S OBJECTIVE

At the feasibility stage of the scheme development, it came to light the need for regulating and controlling the power flow from the BGHES across the 400kV outgoing lines towards Zimbabwe, due to multiple parallel connections. The study's objective was to confirm the suitability of the proposed BGHES transmission scheme with power flows compatible with the interconnected network operation of the target scenario (as shown in figure 2), based on a combined asset of the two national grids with power export. The unit commitment considered for balancing the grid load demand (4,620MW in Zambia, 4,510MW in Zimbabwe, 920MW of

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export) consists in generated output of 11,370MW split in 117 units, with 4.8% of losses, mostly owing to transmission system.

The following were recognized as specific driving requirements:

- controlling transmission capacity with routing capabilities to different directions discriminating the path on the basis of actual load configuration of the Zimbabwean grid, regardless of power regulation made at Batoka; this scope is not achievable by generating units regulation, which does not allow to discriminate "per circuit" power flow
- allowing flexibility and reliability of the scheme

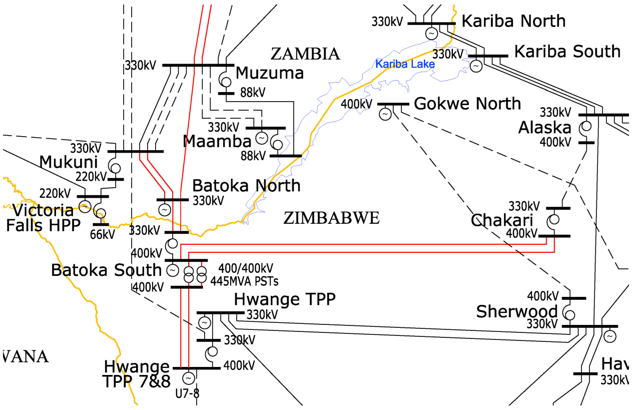

Fig. 2. BGHES transmission system topology

It was also believed at the beginning of the assignment that, PST technology would have been the only means for achieving the desired control of power flow towards Zimbabwe in an efficient and safe manner, without increasing grid complexity. The power flow optimization incurred in the challenging adoption of PST technology to manage the share of the generated power on the lines departing from the Batoka substation (Zimbabwean side) in southward direction. A "power congestion" could happen at the existing Hwange thermal power plant, presently under upgrading from 840MW to 1,440MW. The introduction of the PSTs at the bus departure of the lines to Hwange (2 lines, ~70km long, 400kV) enables power flow control on these lines and, for a principle of complementarity, the power to a different bus (Chakari, 2 lines ~410km long, 400kV) eastwards.

In light of the above, the authors have proposed the insertion of two PSTs, interposing this type of electrical machine between the 400kV bus at Batoka sending end and two specific outgoing lines towards Zimbabwe (to receiving end in Hwange). The paper deals with the description of the preferred scheme, agreed with the ZRA and the national utilities, and the considerations that led to its selection.

III. SCREENING OF AVAILABLE TECHNOLOGIES

As the above-mentioned task can be performed by several Flexible AC Transmission Systems (FACTS) controllers, their effectiveness in doing it can vary, substantially [2], [3]. The following classification offers an overview of FACTS devices application and relevant system conditions wherein they are conceived to be operated, together with specific cost. Depending on the way FACTS devices are connected to a power system, they can be divided into shunt and series devices, being the latter purposed to series compensators, phase angle regulators and power controllers.

Whenever power flows between two network buses, there is a modulus change and a phase angle difference between sending and receiving end voltages. If the systems are connected in two or more parallel paths so that a loop exists, any difference in impedance will cause unbalanced line loading, so that:

i. MW flow is proportional to voltage phase angle difference

ii. MVAR flow is proportional to voltage modulus difference.

Consideration has been restricted to those providing similar functions to PSTs, i.e. power flow control entailing the following main features, capabilities, and specific costs (estimated procurement costs in USD as per year 2018):

a) Static VAR Compensator (SVC), Static Synchronous Compensator (STATCOM): issues addressed, among others, steady-state voltage control, dynamic and post-contingency control, power oscillations damping, transient stability improvement, power quality improvement; main features of fast acting continuous control, robust control algorithm needed, high dynamics and voltage fluctuations; cost ranging 35-60kUSD/MVAr

b) Series Capacitors (SC), Static Synchronous Series Capacitor (SSSC): Steady-state voltage control and load sharing improvement; featuring continuous control with low losses; 25kUSD/MVAr (SC), 40-60kUSD/MVAr (SSSC)

c) PST: Steady-state load sharing improvement, post-contingency load sharing; 7-20kUSD/MVA (The specific cost hereby given refers to the design power and not to the throughput power. In the latter case, the specific cost results much lower)

d) Thyristor Controlled Series Capacitors (TCSC): post-contingency load sharing, power oscillations damping; featuring Fast action, insensitive to localization; 40-60kUSD/MVAr

IV. JUSTIFICATION OF PST TECHNOLOGY

If a PST is inserted into one of parallel lines it is possible to control MW and MVAR flow with a respective phase shift on-load tap changer (OLTC, in-quadrature regulation) and voltage tap changer (in-phase regulation, whenever needed) [3], [4], [5]. Basically, a phase shifting transformer creates a phase shift between the primary (source) and the secondary (load) side, purposed usually to power flow control in complex networks, by injecting an in-quadrature voltage component regulated by mechanical tap-changer switches.

Although the technology is relatively old, the PST proves to be a valuable and reliable system strategy of power flow control, among the devices capable of power flow control without direct intervention on network topology, evidencing robust application worldwide. It also allows to mitigate unbalanced loading of parallel lines with same power flows but different in length (impedance). Its application finds key features in low cost, traditional technology use, reliability, very low maintenance implications. It represents quasi the most important device in open market context for energy transport and power flow regulation among multiple partners in many multi-country systems such as ENTSO-e in Europe, Brazil, United States, Japan, etc [5], [6].

Leaving to specialized literature any theory detailed appraisal of PST functioning, its safe and rational operation has been investigated as part of this network study, seeking power flows regulating effects across the interconnected network of Zambia and Zimbabwe, while assessing benefits and desired effects on the BGHES.

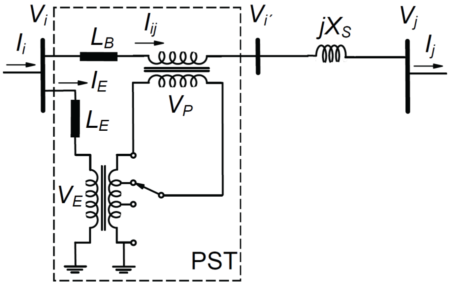

Fig. 3. PST' series-exciter units schematic diagram

The screening of the applicable solutions showed that the installation of PSTs in the BGHES with an in-quadrature voltage regulation of relatively small angle range has been found technically satisfactory and prospectively rather cheaper than using other technologies. This is particularly true due to the expected low short circuit currents of the Batoka system (which implies PST lower short circuit impedance and, therefore, lower cost). On the other hands, PST would avoid potential inconveniences related to most of the other series FACTS applications in Zambia and Zimbabwe, such as higher investment and operation and maintenance (O&M) costs and complexity-related issues, introduction of a new technology in the countries, need for special studies including sub-synchronous resonance risk assessment of generators of thermoelectric plants, possible worsening of transient state behaviour of the Batoka – Hwange tie-lines due to FACTS regulators dynamics.

The ultimate selection of the PST machine type (symmetric or non-symmetric, a quadrature or non-quadrature, with single or dual core design as shown in figure 3, and finally with single tank or dual tank design) and the specific insertion scheme have been made also in consultation with experienced available manufacturers on the market.

V. RESULTS

PSTs are devices able to exercise control on the flow of power across a transmission line and consequently on the network, by means of redistributing the power across the different circuits of the network.

With reference to the sketch in figure 4 and the vector diagram in figure 5, the active power (P) flowing through across the line reactance (X_L) with Vs and Vr respectively sending and receiving voltages, with an interposed PST with reactance X_{PST} and phase angle difference α (alpha) is given by the following equation (1).

$$P = \frac{V_s \cdot V_r}{X_L + X_{PST}} \cdot \sin(\delta + \alpha) \tag{1}$$

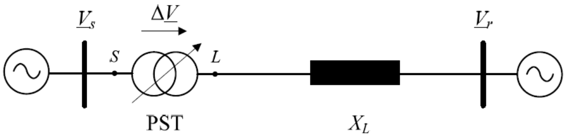

Fig. 4. PST interposition on the controlled line

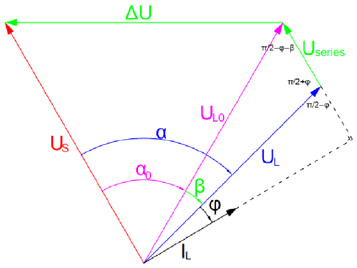

Fig. 5. Symmetric type PST phase S vector diagram (no-load angle α_0), lagging load current

By interposing two 400/400kV PSTs between the 400kV Batoka South bus and the bus of the outgoing lines to Hwange, it is possible to regulate the power flow across these lines and, consequently, the parallel line to Chakari (Batoka node is linked to Chakari by a 400kV line, 410km long).

This has been demonstrated by modelling a PST in the network study and running several load flows with relevant voltage regulation through the entire operating range from minimum to maximum power flow across the Batoka South – Hwange 400kV OHLs.

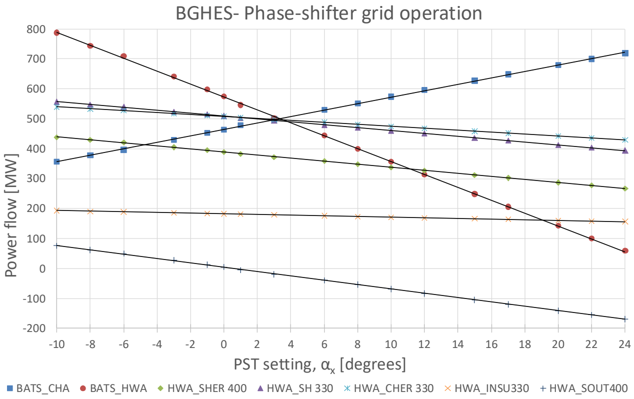

Fig. 6. Regulating chart of power flows across the lines pertaining to the nodes of Batoka and Hwange vs. PST on-load angle (α_x) variation

Software simulations results have been validated by calculations with algorithm based on P-V-angle relationships, as shown in the plot of figure 6 above. Target scenario accounts for export towards Namibia, South Africa (~450MW) and Tanzania, while neglects any dynamic regulating contribution from border countries. The impact of the power flow control by PST regulating angle (alpha), from BGHES South towards Hwange and Chakari nodes, has been assessed over the full range of power transfer of interest. The system exhibits a "natural" power flow without PST, from BGHES South bus, of 657MW and 423MW respectively towards Hwange and Chakari.

VI. DISCUSSION

The analysis returned some recommendations and considerations, among which:

POWER FLOW STEP RANGE. As the natural power flow without PST is about 660MW to Hwange and 420MW to Chakari, corresponding to $\alpha = -3°$ and since the assessed PST regulating field varies from +24° (almost 0MW) to -10° (about 800MW) on the Hwange OHLs, it has been recommended to select an on-load regulating range of ±10°, corresponding to the control range 350MW to 787MW. The quadrature OLTC should therefore have a stepping capability of about 21MW/tap, i.e. 21MW/° of angle alpha, acceptable by any manufacturer, whereas the range of ±10° can be realised with ±8x1.18° and three 1-ph OLTCs [7].

POWER RATING. PST series units combined rating matches the maximum allowable power flow through the two 400kV OHLs to Hwange, as assessed to be ~790MW under this study. Therefore, by considering also economic reasons and available commercial sizes, two units are proposed with a throughput power of 400MW each (445MVA). The preliminary dimensioning power is 230MVA. Expected no-load and load losses range respectively approx. 90-110kW and 580-620kW per unit. Simulated operating losses are recorded as high as 1.1MW per unit at nominal loading, i.e. 0.18% of the BGHES South plant capacity.

PST TYPE. Despite the initial consideration given to the "asymmetric quad booster" type, avoiding in-phase regulation allowed choosing a simpler machine of the "symmetric" dual-core type, well-fitting the purpose of the proposed angle regulating range with negligible variation of the voltage output and with remarkable benefits in transport and cost. The machine consists of a 400/400kV 3-ph series transformer, and a 400kV 3-ph shunt (exciter) transformer, oil-filled bus duct-connected. Two PSTs of the dual-core (separate exciter) type with in-quadrature OLTCs will operate in parallel. Having the dual-core PST design short-circuit impedance the sum of the series and the exciting unit (negligible) elements, this has been evaluated in ~8%, nearly constant and not much affected by the OLTC position and herewith by the actual phase shift.

SHORT CIRCUIT IMPEDANCE. PST operation has been simulated with a short circuit impedance of 11%; power flow has been assessed as rather insensitive to its variation, decreasing by 0.5MW per each percentage of PST' short circuit impedance reduction (0.5MW/%).

INSERTION SCHEME. As shown in the single line diagram of figure 7, the two PSTs will be installed at Batoka South Substation (Zimbabwe) in two dedicated bays. Each PST will be inserted by a tie-connection to the corresponding Batoka – Hwange line bay, by a traditional double-busbar scheme with two disconnectors and one breaker on the busbars side, one breaker and one disconnector on the line side. Further to switching studies outcomes, in order to assure recovery of the steady-state load flow after tripping of one of the two PSTs, each line bay is provided with an additional circuit breaker on the busbars side, to allow fast closing and by-passing of the PST in case of tripping.

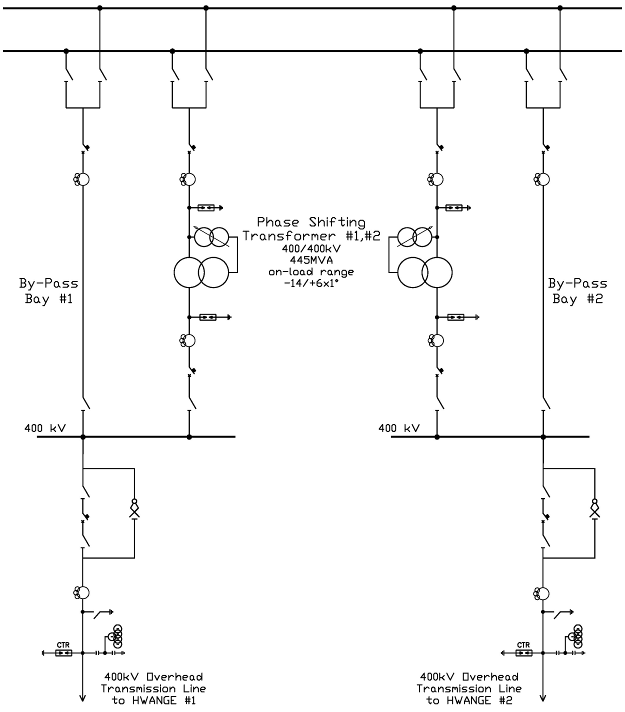

Fig. 7. Single line diagram of the PSTs bays with by-pass

As a further step in PST's engineering, operating consideration has been given also including the second planned 400kV parallel line between Batoka South and Chakari. In doing so, provided that the equivalent impedance seen by each PST results slightly reduced (due to the second parallel line), the same above considerations still apply, with minor tuning, i.e.:

- the natural power flow without PSTs (585MW to Chakari) decreases to the on-load angle $\alpha = -4°$;
- the same power flow control is realized with -14° to +6° range, corresponding to the in-quadrature stepping capability of 22.5MW/tap, i.e. 22.5MW/°, with tap changer on-load range +6/-14 x 1°.

VII. TRANSIENT STABILITY EVALUATION

PST's engineering included transient stability behaviour assessment of Batoka HES against PSTs' contingency, in a 5th order, 300-bus model, with an overlook to operating conditions ruled by SAPP and national utilities grid codes [8], [9]. The following events are here reported:

i. 3-ph bolted fault at Batoka South 400kV bus and tripping of one PST unit at fault clearing

ii. 3-ph bolted fault at Batoka South 400kV bus, tripping of one PST unit at fault clearing and by-pass closure 120ms after fault clearing

In both events the 2nd unit remains in service after tripping of the 1st unit. Event ii., here presented in figure 8, 9 and 10, reflects real operation dynamics of PST by-passing scheme in the credible event of PST's trip due to internal fault or to any other cause triggering unit bypassing.

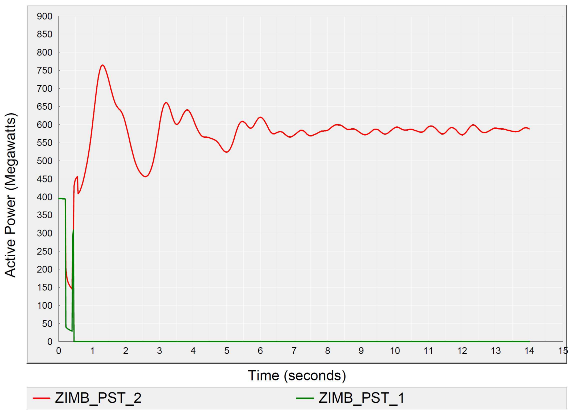

Fig. 8. 3-ph fault at PSTs' 400kV bus, 1st PST tripping followed by its by-pass closure while the 2nd PST remains in service; PSTs power output plots

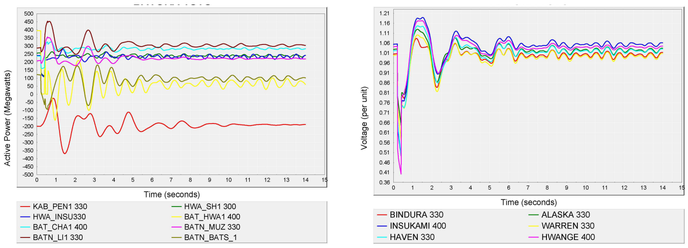

Fig. 9. 3-ph fault at PSTs' 400kV bus, trip of one PST and by-pass closure –plots of power flow across some lines (left) and buses voltages (right)

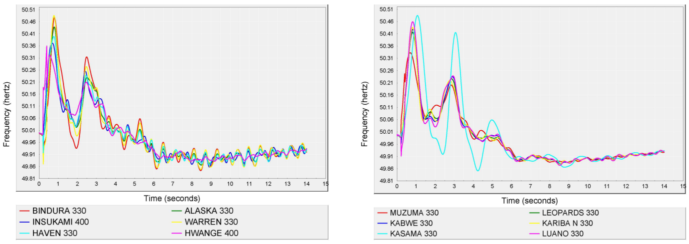

Fig. 10. 3-ph fault at PSTs' 400kV bus, trip of one PST and by-pass closure – plots of system frequency at buses in Zimbabwe (left) and Zambia (right)

Power flow continuity from Batoka South towards Hwange is still retained by the 2nd unit in parallel operation to the by-pass. PST's pre-contingency power flow is about 395MW and 20MVAr, totalling 790MW, on-load angle -12°. Power flow on Batoka – Chakari OHLs is 2x235MW.

Transient stability is preserved up to fault clearing time of ~200ms, as evidenced in figure 9 and 10. By-pass closure allows restoring additional 210MW towards Hwange across the Batoka – Hwange OHL #1. The 2nd PST still in service regulates its own angle from 5.4° to 1.2° stepping down in about 30s (~6s/°) decreasing from 580MW as shown in figure 8 (within IEC-compliant short term loading capability [10], [11]) down to the set-point power of 400MW, as it can safely continue serving regulation to Zimbabwe (any regulation to Hwange implies power re-distribution to Chakari). Batoka – Chakari 400kV OHLs flow increases to 2x290MW.

VIII. CONCLUSIONS

Unconstrained power flow evacuation from the newly conceived BGHES was among the key objectives of the engineering studies tailored to the Zambia – Zimbabwe interconnector. This paper reports the main outcomes in assessing PSTs' connection scheme viability, proposed and conceived in the framework of the BGHES Project. PST's technology and the custom-made insertion scheme are deemed flexible, effective and purposed to the required power flow regulation capabilities across the interconnector, expressing simplicity and economics criteria.

The dynamics of the proposed PSTs scheme during large disturbances, as assessed in the transient stability studies, is remarkable, while the study's conservative assumptions leave room for noteworthy performances once implemented.

ACKNOWLEDGMENT

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