CONTROL MEASURES TO ENSURE DYNAMIC STABILITY OF THE CAHORA BASSA SCHEME AND THE PARALLEL HVAC SYSTEM

W. Bayer, K. Habur, D.Povh — Germany
D.A Jacobson — Canada
J.M.G. Guedes — Portugal
D. Marshall — South Africa

INTRODUCTION

The paper discusses parallel operation of a 1500 km bipolar HVDC link and a relatively weak parallel 400 / 330 kV AC link. Stable operation can be ensured by use of thyristor switched braking resistor and control of the voltage angle difference between sending and receiving end. During critical contingencies dynamic splitting of the HVDC and AC link at the sending end is necessary with respect to stability.

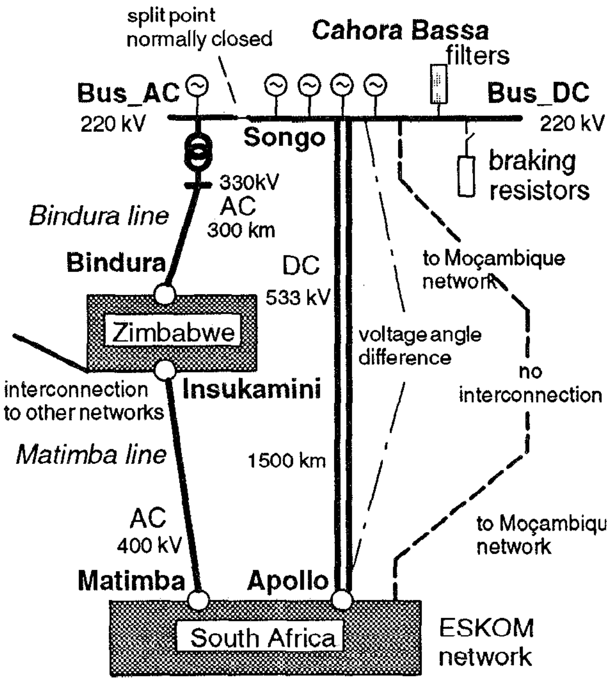


Fig. 1 : Principle Network Configuration

TASK DESCRIPTION AND SUMMARY OF RESULTS

The study deals with the stabilization of the planned Cahora Bassa – Zimbabwe – South Africa interconnection. The 220 kV busbars at Songo are coupled and the AC and DC systems between Songo and South Africa are operated in parallel. This offers technical and economical advantages in operation. Maximum generation at Cahora Bassa is 2000 MW.

The AC / DC interconnection can improve the stability of the Zimbabwe network substantially compared to operation with an open busbar coupler at Songo. Improved stability is achieved by utilizing DC power to rapidly control the voltage angle difference between Songo and Apollo. This permits system operation with voltage angles of the order of 60 deg.

Disturbances from the DC side such as commutation failures at Apollo and DC line faults affect the AC system (Zimbabwe). The operational requirements during contingencies are:

- no loss of rotor angle stability
- damping of power oscillations in the AC link
- limitation of transient voltage drops (except during short–circuit)
- infrequent switching operations (busbar splitting) at Songo due to disturbances

These requirements are not fulfilled unless special countermeasures are carried out.

A combination of the following countermeasures will meet the above requirements:

- use of a thyristor switched braking resistor (480 MW)
- use of a breaker switched braking resistor (240 MW)
- control of voltage angle difference by braking resistor and DC power modulation
- dynamic busbar splitting (only in exceptional cases)
- Bindura line tripping (only in exceptional cases)
- tripping of generators (only in exceptional cases).

Voltage angle control requires synchronous angle measurement at Songo and Apollo which can be verified by use of the GPS (global positioning system).

Cahora Bassa system operates in angle control mode or in frequency control mode when the AC link is interrupted. Automatic change over of control modes and resynchronization after interruption of the AC link (Cahora Bassa – Zimbabwe – South Africa) is provided.

Design considerations for the controls are robustness, transparency and insensitivity against failure of equipment or loss of relevant control parameters.

'AC and DC Power Transmission', 29 April–3 May 1996. Conference Publication No. 423, © IEE, 1996

BASIC REQUIREMENTS FOR STABILIZATION OF THE AC LINK

The DC transmission is subjected to a relatively large number of disturbances (commutation failures and DC line faults with or without successful restart). More than 1 fault per day cannot be excluded according to former operation experience.
The AC link on the other hand is weak because of the long distance. The power change is of the order of 7 MW per degree change of voltage angle. Therefore the AC link can absorb only a small quantity of the load deficit caused by faults on the DC transmission. Braking resistors are therefore necessary to keep the power balance at Songo.
Apart from stabilizing the AC link, the braking resistors prevent frequent generator tripping which is undesirable with respect to the service life of the generators.

In addition to sufficient braking power a suitable control criterion is required. The power in the AC link does not reflect adequately the deviation of the Songo–Apollo angle because of transients between the Zimbabwe and the ESKOM networks (Fig. 1). Therefore the measured angle difference between Songo and Apollo is used as control criterion. The voltage angle between Songo and Bindura which has the advantage that it can be calculated from locally measured variables at Songo is no adequate substitute for the measured angle Songo – Apollo.

GRID MASTER POWER CONTROLLER (GMPC)

The control functions for power balance and grid stabilization are combined in the GMPC.

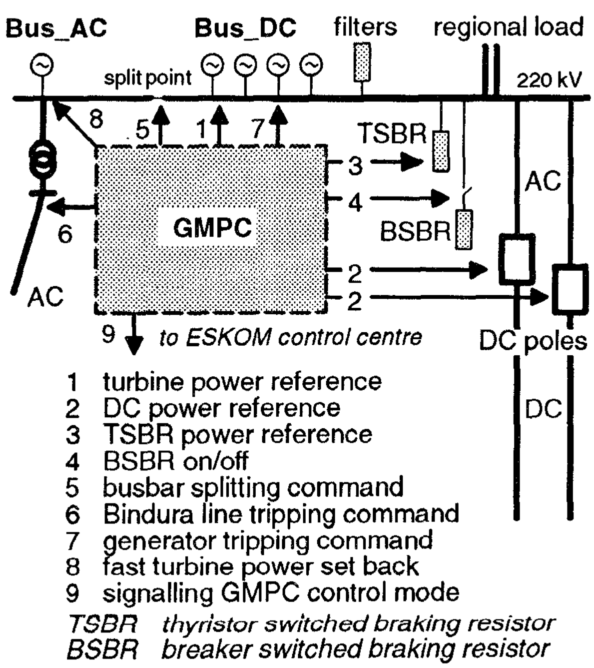


Fig. 2 : Selected Outputs of GMPC

Fig. 2 shows a selection of relevant GMPC output variables. The most relevant equipment and controls related to network stabilization are described in the following sections.

VOLTAGE ANGLE DIFFERENCE AS CONTROL CRITERION

The control criterion has the following advantages:

- Independence on transients in the Zimbabwe network and its interconnection to other systems
- Controlled bumpless reconnection of the AC link after line tripping due to line faults
- Reliable operation at high voltage angles of 60 deg and above
- Possibility to interconnect other weak ties between Songo and ESKOM (through Moçambique) as traced in Fig.1 in the eastern area.

Power oscillations develop between Songo and ESKOM via the Zimbabwe network. The oscillations are damped by measures at Songo (modulation of braking resistor power and DC power).

Other oscillations which develop mainly between Zimbabwe and ESKOM are also reflected to Songo. However, the possibilities to damp these oscillations by measures at Songo are limited as Songo is located far away from the areas where the oscillations occur. These oscillations can be damped by adequate measures in the Zimbabwe network.

After multiphase faults on the single line part of the AC link the interconnection between Songo and ESKOM via AC is interrupted. Automatic high–speed reclosure could be applied, however, only within certain limits of the angle difference across the split point. Moreover there is the risk of unsuccessful reclosure.

With the angle control an automatic delayed reclosure can be carried out in a controlled way such that the reclosure is bumpfree. Unsuccessful reclosure does not worsen the situation with respect to rotor angle stability.

The interconnection can be operated at relatively high voltage angles between Songo and Apollo. The maximum steady state angle in the studies was 54 deg. However, this is not a limit with respect to rotor angle stability. The limitation is only caused by the transient voltage deviation in the Zimbabwe network which should not exceed 10 %. Rotor angle stability could be achieved at much higher angles as the angle control provides always correct control signals also beyond 90 deg.

From both the Songo and the ESKOM networks tie lines also exist into the Moçambique network. These lines could not be interconnected up to now as they would not develop sufficient synchronizing power to keep Cahora Bassa and ESKOM networks in synchronism. With angle control between Songo and Apollo stability can also be achieved for weak tie lines.

The expected time delay for sending the voltage angle from Apollo to Songo is 50 – 90 ms including measurement and data processing.

BRAKING RESISTORS (BR)

The BR serve a double purpose.

Stability Control

BR are well suited for keeping the angle at Songo within acceptable limits. However, the stabilizing task during operation with AC interconnection requires faster reaction and better controllability than the task to keep the frequency in isolated operation within the given limits.

The examined worst case condition in the network studies is: operation with all 5 generators (2000 MW), 4 + 2 DC bridges on the 2 poles (2 bridges out of service), fault on the DC line with 4 bridges and unsuccessful restart attempts. This requires a total of 720 MW BR capacity.

Different types of BR have been examined. The selected solution was a total braking resistor power of 720 MW where at least 2/3 or 480 MW are thyristor switched. With respect to stability there was no relevant difference between the effect of either a thyristor controlled braking resistor (TCBR) which is controlled continuously or a thyristor switched braking resistor (TSBR) which is controlled in steps of approx. 70 MW (reference Fig. 3).

The TCBR or TSBR is used whenever the generated power exceeds the capability of the DC poles and the AC link to pick up load as the number of insertions is not restricted. On the other hand insertion of the Breaker Switched Braking Resistor (BSBR) is delayed such that the BSBR is not inserted during the relatively frequent commutation failures with normal restart of DC power. However, the delay of insertion is a disadvantage in cases with delayed power restart as this cannot be predicted. Here fast insertion of the braking resistors is important as the angle deviation during a contingency is proportional to the double integral (over time) of the power imbalance between generated power (turbine power) and load (generator power). Therefore a compromise between sufficiently fast insertion on one hand but not too frequent insertions on the other hand is strived for. The final setting is left to operational experience.

An alternative where the total braking resistor power is under thyristor control would (except redundancy aspects) offer the following advantages:

- faster insertion
- no limitation of number of insertions (no breaker switching)
- availability for several insertions in quick succession (e.g. if DC line faults are caused by oscillating trees).
- good controllability especially for damping of power oscillations in the second range.

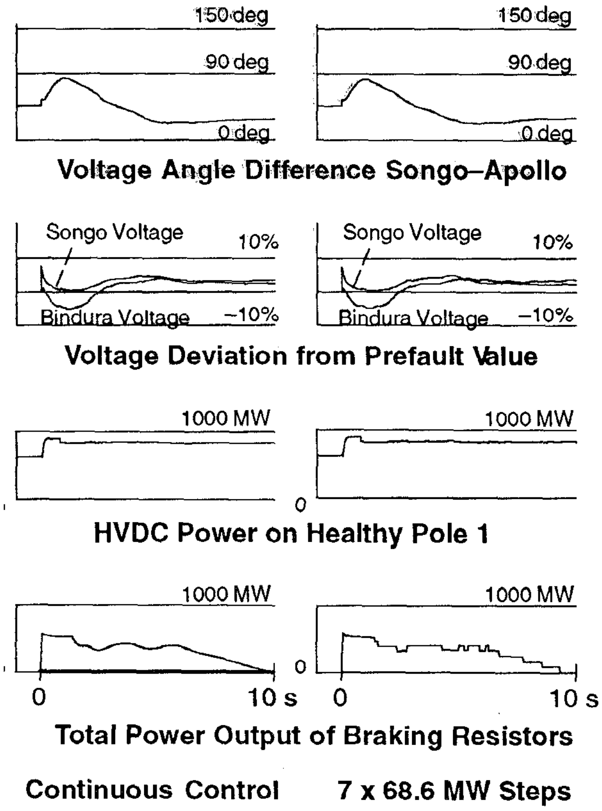


Fig. 3 : Comparison of Continuous or Stepwise Thyristor Control of Braking Resistors

Prevention of Generator Tripping

In former operation the planned AC link Songo – Zimbabwe – ESKOM as shown in Fig.1 did not exist. Cahora Bassa was an isolated power plant with independent frequency.

Frequent DC line faults with unsuccessful or delayed power restart resulted in frequent generator tripping as the overload capacity of the DC poles was (apart of short transients) limited to 105% I_n and the transiently available frequency range is limited to 50 ±1 Hz. Because of the negative effect of frequent generator tripping on the service life of the generators application of 240 MW BR was already considered in former isolated operation.

POWER CONTROL

Fast Control

Power Balance Control. Rapid power balance adjustments are necessary following severe disturbances (i.e loss of DC pole) in order to maintain stability. The required power insertion is calculated quickly and is provided by any available DC overload and braking resistors. The control is in principle a temporary feedforward correction. Feedback controls are provided by the power modulation controls for permanent fine tune power adjustments.

Power Modulation Control. The power modulation control adds to the output of the power balance control transient components which stabilize the voltage angle at Songo (PD controller). The P–component provides the synchronizing power, the D–component provides damping of power oscillations.
In steady state operation the output of the power balance and the power modulation controls is zero.
The total transient power requirement is passed to the load joint control where the load is distributed to the HVDC poles and the braking resistors.

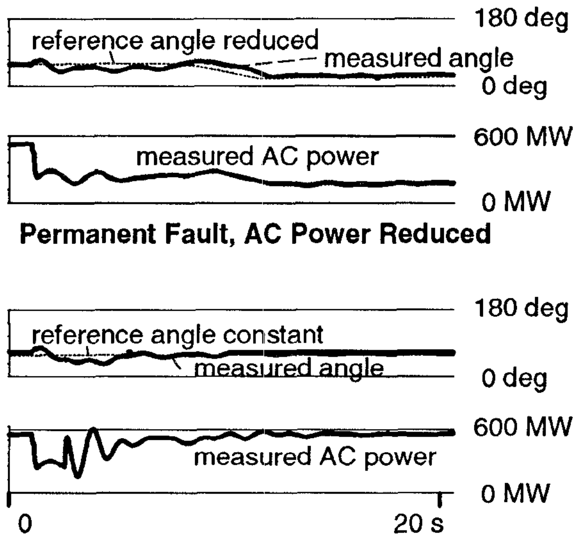
The fast control is responsible for stabilization during contingencies.

Slow Control
The load demand from the AC and the DC links is checked against the power transfer capability of the links and the available generation. Then the reference values are defined. The required total generation is distributed to the individual generators. Individual upper limits can be set. This allows for example to avoid working points of the turbines where cavitation occurs. Moreover, any generator can be taken out of the joint control and be operated manually.
In case of sudden changes of load or generation (e.g. trip of a generator or DC line fault without power restart) the new reference values are calculated and adjusted under consideration of the maximum rate–of–change capability of the turbine power.
If the total power demand is higher than the generation capability the AC load has priority.
The control of the power in the AC link is performed by slow integral control of the angle reference value of the PD controller. The maximum steady state angle is limited to a value set by the operator. If the Zimbabwe network cannot (for any reason) absorb the required power within acceptable angle limits the power flow in the Bindura line is reduced accordingly.

FAULTS IN THE AC LINK

During 1phase faults in the Bindura line (with rapid single phase auto–reclosure) 250 MW braking resistor power are inserted for about 1 s until the faulted phase is reclosed. 1phase faults on other lines do not require control intervention at Songo.
After 3phase faults (without high–speed reclosure) on the Bindura line 480 MW braking resistor power are inserted. Then the turbine power is set back by the amount of the lost line load and the braking power is removed accordingly. The signal for insertion of braking power originates from the line protection.
After 3phase faults (without high–speed reclosure) on the Matimba line the Bindura line provides the power balance and the DC power is adapted accordingly. The total load in the interconnected system and the generation at Cahora Bassa remain unchanged. Only the distribution of power flow from Cahora Bassa to the grid via AC and DC links is changed.

There are other possible AC line trippings within the Zimbabwe network which limit the power the system can absorb from Songo. Such faults are detected by a logic which provides braking resistor power and ramps it down to zero after elapse of a few seconds.
In case of transient line faults the voltage angle at Songo remains within preset (acceptable) limits and the steady state power flow to Bindura keeps the pre-fault value. Reference lower diagrams of Fig. 4.



Transient Fault, AC Power not Reduced

Fig. 4 : AC Power Flow in the Bindura Line after a Fault in the Zimbabwe Network

In case of a permanent line trip the angle exceeds a set limit. As a consequence the power in the Bindura line will be reduced to a value which the Zimbabwe network can absorb. Reference upper diagrams of Fig. 4.

DYNAMIC ISOLATION OF THE AC AND DC NETWORKS

The bus coupler at Songo is normally closed (Fig. 1). However, if the stabilizing measures at Songo are not sufficient during contingencies the AC and DC networks are split. For the faults coming from the DC side (commutation failures and DC line faults) the bus coupler is the suitable split point. These faults are expected to be the more frequent and critical ones. For faults coming from the AC side (Bindura line and lines within the Zimbabwe network) the line breaker at Songo is the preferred split point.

The number of dynamic network splittings shall be limited to the order of 10 per year for operational reasons. The task is to avoid unnecessary splitting but to split as fast as possible if necessary. Different strategies have been examined including a prediction method where the development of a disturbance is continuously assessed for the future (approx. 100 ms) and where the assessment is continuously corrected for the past.

However, under consideration of all aspects, especially robustness, a relatively simple method has been used. It is based on an assessment of the generated power (turbine power) and the capability of the network to absorb load. The difference is accumulated over the time. If a set limit (MWs) is reached busbar splitting is executed.
An angle dependent splitting criterion serves as backup.

Other contingencies where busbar splitting is executed are:

(1) Multiphase faults on 220 kV lines close to Songo which are not cleared in the first protection zone. The criterion is the positive sequence voltage at Songo.

(2) Loss of the filters. Immediate busbar splitting separates the AC loads from the DC poles which are the source of uncompensated harmonics now.

(3) Complex disturbances and / or loss of relevant control functions.

For the dynamic isolation of AC and DC networks 2–cycle breakers are considered.

CONTROL MODES

Angle or Frequency Control

The normal control mode in parallel AC / DC operation is angle control.
In isolated operation (no AC / DC interconnection) the frequency at Songo is controlled to 50 Hz with respect to the small steady state frequency band of the filters of 50 ± 0.5 Hz. The controller is of the PID type.

The switching state of the AC link (parallel to DC or not) is derived from the switching states of the bus coupler at Songo, the Bindura line and the Matimba line. The first 2 states are available as local criteria. The last one must be signalled from ESKOM control centre to Songo.

Interconnecting Control

Interconnecting control is an auxiliary control mode for transition from Cahora Bassa island operation (with frequency control) to interconnected operation Songo – Zimbabwe – ESKOM (with angle control). The purpose of the interconnecting control mode is

- to make the interconnecting procedure easier for the operator
- to reduce the risk of malfunction (loss of rotor angle stability).

2 different interconnection procedures are considered.

If the Matimba line was tripped the Insukamini line end is closed after the transients have died away. The disturbance by a possibly unsuccessful reclosure does not add to the first disturbance where the line has been tripped.
If the line reclosure is successful a paralleling device at Matimba is prepared to reconnect the AC link if the criteria (frequency, angle) are fulfilled. The interconnecting control at Songo provides these criteria by controlling the frequency at Songo to the ESKOM frequency minus 50 mHz for example. Then the paralleling conditions at Matimba are fulfilled latest after 20 s. The course of paralleling is bumpfree.

Two signals are exchanged between Songo and ESKOM control centre for this purpose.
(1) A release signal from Songo to Matimba indicates that the controls at Songo are ready to change from frequency control (in isolated operation) to angle control (in parallel AC / DC operation). Reconnection of the AC link while Cahora Bassa stays in frequency control must be avoided as it would result in loss of stability.

(2) Closing of the AC link at Matimba is indicated by a signal sent to the Songo controls. Consequently the control mode changes from interconnecting to angle control and the busbar splitting logic which was blocked during isolated operation (frequency control) is reactivated.

TELECOMMUNICATION REQUIREMENTS FOR STABILITY CONTROL

The stability controls at Songo are based on locally available control variables as far as possible. However, the following variables and signals from remote locations are required at Songo:

- Voltage angle from Apollo (1500 km distance) with a time stamp. The arriving angle is combined at Songo with the according local angle measurement in order to get the angle difference Songo – Apollo.
- Matimba line switching state.

From Songo to ESKOM control centre a release signal is transmitted which indicates that the Matimba line can be closed for AC / DC parallel operation.

BACKUP FUNCTIONS FOR STABILITY CONTROL

Stability of the AC link is maintained by control devices. Therefore backup functions are provided in order to minimize the risk of instability as far as possible.

The angle from Apollo to Songo is transmitted on 2 different paths (2 DC lines). Plausibility controls are provided.

However, during commutation failures both paths may be distorted by flash over in the earth wire which serves as carrier. In this case the prefault angle difference is frozen and the frequency at Songo is used for power oscillation damping.

If the indication of the switching state of the Matimba line is uncertain, the state is interpreted as closed. Assuming that the real state is open, this would result in erroneous operation in angle control which does not affect stability.

The opposite, erroneous operation in frequency control (assuming open AC link) while the link is in fact closed would result in instability and must therefore be prevented. This may happen if during the interconnection procedure the line–on–signal from Matimba does not arrive at Songo. As stability should not depend on a switching state signal received from a remote location a backup function is provided.
Before the AC link becomes unstable the power in the Bindura line will decrease in a characteristic way. This is used as a local criterion to change the control mode immediately from interconnection to angle.

It is not practical to check the controls for any fault in the network, any disturbance of equipment and any combination thereof.
Adequate controls have therefore been provided and checked only for contingencies with a relatively high probability of occurrence or where application of suitable remedies is easy.
In all other cases where there may be a hazard to stability preventive busbar splitting is executed. This eliminates stability problems between AC and DC link presupposed that the splitting occurs in time. The number of such events is assumed to be small.

In a number of study cases the generator connected to Bus_AC (reference Fig. 1) was subjected to slowly increasing power oscillations after the busbars are split. After busbar splitting it is no longer possible to damp these power oscillations by modulation of DC and / or braking resistor power as these are connected to Bus_DC.
However, as the oscillations develop relatively slowly, a reduction of the turbine power of the generator on Bus_AC will result in damping of the power oscillations.

GENERATOR TRIPPING

Generator tripping is the last remedy to keep the power balance. It should occur only in rare contingencies (e.g. if a braking resistor is not available). The number of generators to trip is calculated from the power balance control. If more than 1 generator should be tripped, only 1 generator is tripped after elapse of 190 ms and the busbars are split instead of tripping more generators. The rest of generators selected for tripping are prepared for frequency dependent tripping where the tripping frequencies are set dynamically such that the upper frequency limit for tripping of the filters is not violated. This procedure was found as a compromise of the following requirements:

- minimize generator tripping
- prevention against spurious tripping
- selective tripping
- avoid filter tripping
- avoid frequent busbar splitting.