GMPC Enables Energy Transmission Over Interconnected SAPP Grid

Pieter V. Goosen, Peter Riedel, and John W. Strauss

***Abstract*—The grid master power controller (GMPC) controls the generation at the Cahora Bassa hydro power station in Mozambique and its dispatch through parallel ac and dc interconnections. The bulk dc power flows directly to South Africa while ac power is delivered to Zimbabwe that is also interconnected with the South African ac grid. This paper describes the GMPC functions in its various control modes that are required for the system configurations.**

It features adaptive gain and offset compensation for precision open-loop control of the HVDC and the turbines; robust control strategies for nonresponsive generation or transmission; fast GPS-based angle measurement for damping control; robust automatic control-mode-selection independent of remote signalling; controls for proposed braking resistors; and smooth and safe control transfers between the GMPC and its emergency standby controller (EC).

The success of the GMPC is evident from the fact that the "angle control mode" in which the high power HVDC system operates parallel with the weak ac interconnection, has become the unreserved and preferred choice ever since its commissioning in October 1999.

***Index Terms*—Cahora Bassa HVDC, grid master power controller—GMPC, parallel ac/dc operation, ac/dc interconnection, braking resistors, frequency control, angle control.**

I. INTRODUCTION

SECTION I provides an overview of the power system components and the GMPC. Section II discusses operating configurations and related control modes. Section III deals with the functions and features of the GMPC. It also details the challenging conditions related to operating a high power dc system in parallel with a weak ac interconnection both connected to a nonideal and isolated hydropower station. Section IV summarizes the advantages of the angle control mode with Section V illustrating the GMPC's performance with the aid of recorded responses to typical faults initiated during final acceptance testing.

The five 480-MVA generators (Fig. 1) at Cahora Bassa feed into the dual 220-kV busbar substation in Songo 6 km away. The main ac and dc loads are each dedicated to a busbar. The HVDC bus is defined as the "dc bus," whereas the Bindura ac line feeding Zimbabwe is normally connected to the "ac bus." The low power local ac loads (not shown in Fig. 1), that is, two 220-kV lines to Tete in Mozambique and system auxiliaries may be connected to either busbar. The GMPC is prepared for future braking resistors. The 2 × 960-MW bipolar HVDC system is rated for 1800 A and ±533 kV. Each pole consists of four six-pulse bridges each rated for 133.3 kV and 240 MW.

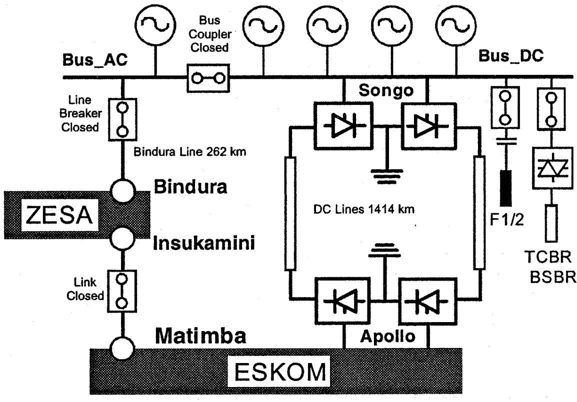

Fig. 1. Coupled operation in angle mode (ZESA-Eskom link closed as shown) or in ZESA mode (ZESA-Eskom link open).

TABLE I
KEY DATES OF CAHORA BASSA SCHEME

May	1972	Diversion tunnel through the North Bank completed
Dec	1974	Filling of the Cahora Bassa lake commenced
Sept	1976	Rotation of the first generator set
June	1979	Commercial operation with 1920 MW HVDC to Eskom
June	1980	Interruption of commercial exploitation
June	1992	Contract 500 MW for Zimbabwe
Dec	1997	Start of ac power delivery to Zimbabwe
May	1998	Pre-commissioning of HVDC in isolated mode
Aug	1998	Restart of HVDC commercial operation to RSA
Oct	1999	Final acceptance tests of GMPC for all control modes

The commercial operation of the final stage of the 1920-MW Cahora Bassa HVDC scheme for delivering power to South Africa originally commenced in June 1979 (see Table I). However, dc line sabotage completely halted operation in 1984 [1]. Renewed commercial exploitation commenced in December 1997 but with the change that 500 MW at 330 kV ac had, in the meantime, been dedicated to Zimbabwe via the new Bindura line. Due to the fact that Zimbabwe had in the meantime also been connected to the South African grid, a weak ac link in parallel to the powerful HVDC system had been created. The original master power controller (MPC) that had been designed for "islanded" HVDC operation had, consequently, to be replaced by the new GMPC.

The HVDC system was restarted in the original island mode with an allocation of three of the five generators. The other two generators (one for security) were dedicated to the then still isolated ac load. In October 1999, the ac, dc, and power station system was finally recommissioned for full commercial operation and with all the functions of the new GMPC activated. This

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P. V. Goosen is with Eskom, Transmission, Johannesburg 2000, South Africa (e-mail: piet.goosen@eskom.co.za).

P. Riedel and J. W. Straus are with Siemens AG, Erlangen D-91052, Germany (e-mail: peter.riedel@siemens.com; john.strauss@siemens.com).

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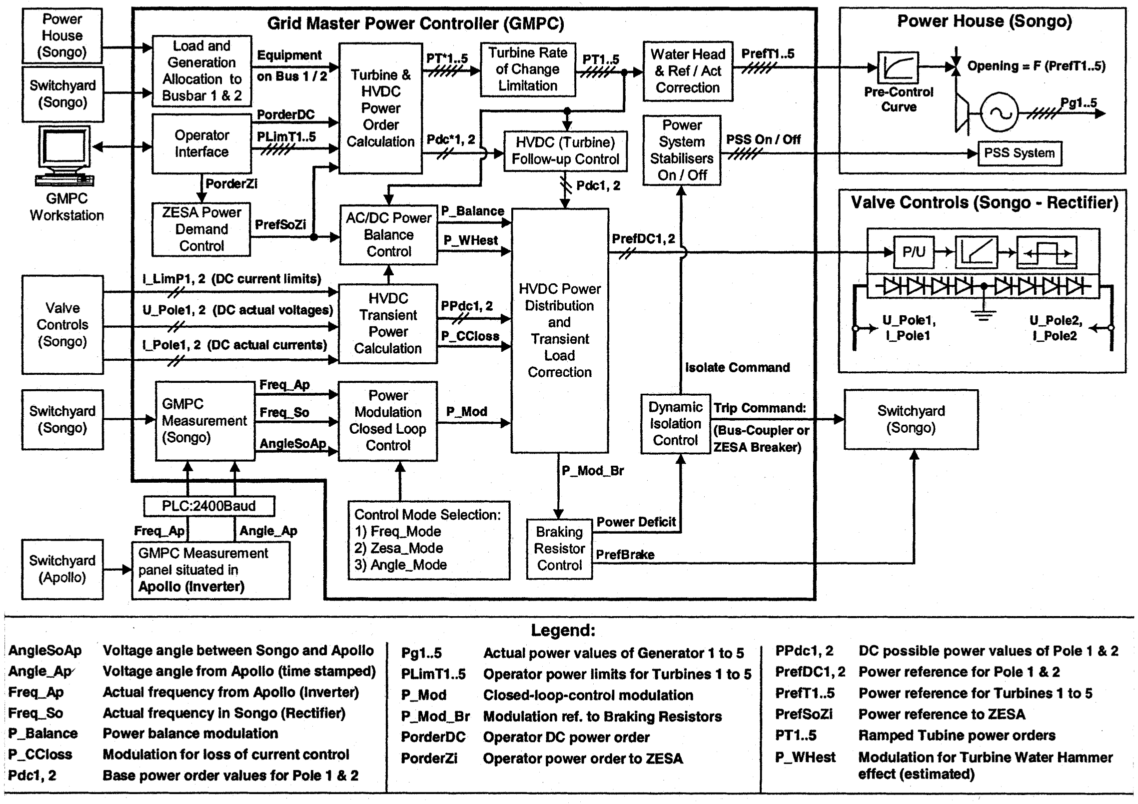

Fig. 2. Software overview with main inputs and outputs of GMPC.

created freedom for optimum exploitation of the ac and dc systems and their shared generation in all possible configurations.

Reference [2] summarizes the GMPC control features for parallel ac/dc operation. These functions were initially tested per TNA and later also with supplementary digital simulations before completing the GMPC's commissioning in 1999 [3]. Although the basic controls established during the design stage and TNA testing remained unchanged, modifications and enhancements were introduced during the digital simulations. These include eliminating dependence on remotely detected ac interconnector statuses; eliminating the special interconnection procedure for closing the Matimba line (Section III.G); enhancing damping of HCB-ZESA oscillations with the derivative of the measured Bindura line power (Section III.D); introducing the "ZESA control mode" (ZESA-Eskom link open) (Section II); implementing the turbine, HVDC, and busbar reference/actual (R/A) correction and supervision; enhancing the Bindura overload protection (Section III.B, E), and the simplification of the ZESA "transient power reduction" functions.

Fig. 2 provides an overview of the GMPC function packages with the relevant inputs and outputs. The main inputs via the operator interface are the ac and dc power orders (PorderDC and PorderZi) as well as the power limitations for the individual turbines (PLimT1...5). The turbine power orders (PrefT1...5) and the base power order for the HVDC poles (Pdc1, 2) are calculated in the GMPC function groups for 'Turbine and HVDC power order calculation'. The power orders that are finally sent to the HVDC control (PrefDC1, 2) include the modulation components which are derived in the function groups for 'HVDC power modulation and balance controls'.

II. OPERATION AND CONTROL MODES

A. Isolated Operation

In this mode, the HVDC system is isolated from the Bindura line by having the bus-coupler in Fig. 1 open. The GMPC controls the turbines on the ac bus to provide constant power to ZESA. On the dc bus, the GMPC maintains exact power balance at 50 Hz by modulating the HVDC output around its base power order depending on the frequency error. Proportional-integral control is used for this "frequency mode" of operation. Proportional characteristics provide fast but course frequency control whereas the integral portion provides the exact, but slow 50-Hz control. A high gain "disturbance controller" (see also Section III.B) takes over from the slow integral controller during large disturbances and ensures that the integral controller is primed with the best initial value at its reactivation after a disturbance.

B. Coupled Operation in ZESA Control Mode

In the ZESA mode (Fig. 1 with ZESA-Eskom link open), the GMPC supplies constant power to the Northern Power Pool and there is no ac coupling with the large Eskom system some 1000 km away. Since the pool frequency is controlled by the connected utilities (totaling approximately 2000 MW), the GMPC's integral frequency controller is disabled and its proportional controller's gain is significantly reduced. Due to its nonlinear gain, the latter controller effectively has a dead-band of ±100 MHz in this mode. This control strategy is necessary because the contractual constant-power requirement for Bindura becomes incompatible with the GMPC exercising frequency control utilizing Cahora Bassa's generation. Operating Bindura at the full power rating of its 220/330-kV coupling transformer leaves no upward control margin for underfrequency support of the ZESA system. Thus, to avoid overloading the Bindura link (as would happen if the HVDC were ordered to release load for countering underfrequency), it becomes essential to disable the GMPC's exact (integral) frequency control and to weaken its proportional frequency control. The remaining weak proportional frequency control outside the "dead band" then only provides "last resort" control for severe underfrequency that may cause splitting of the ac and dc systems.

C. Coupled Operation in Angle Control Mode

In angle mode (Fig. 1), the GMPC stabilizes the parallel ac system by modulating HVDC power as a function of the derivative of the Cahora-Bassa/Apollo voltage angle and the derivative of the Bindura power. The HVDC is essentially operated in a constant power mode.

III. TASKS AND FEATURES OF GMPC

A. Power Order Coordination and Limitation

The GMPC coordinates generation with combined HVDC and Bindura power orders. It prescribes the orders for the HVDC, the Bindura line, and each turbine under its control. Note that contrary to the controlled flows on the Bindura line and the HVDC, those on the Tete lines are determined solely by the connected passive loads. The GMPC gives precedence to ac loads, and therefore, HVDC load is sacrificed until all ac loads, including that set for Bindura by the operator, have been satisfied by the generation. This means that when an "ac" generator trips, its contribution to the ac load is immediately subtracted from HVDC order.

The GMPC limits HVDC and turbine orders to the maximum available generation capacity and the possible power of the HVDC. The latter limit is derived from any HVDC current limitations and the total dc voltage. The HVDC capability may be further reduced by loss of current control in the rectifier or for the purpose of avoiding persistent or intermittent overmodulation into the transient loading range. Additional power limits may be applied in order to avoid overloading the Bindura line or to prevent damage resulting from inappropriate open-loop responses from any of the HVDC poles or the turbines. It is particularly important to guard against offset, gain, and limitation errors in the open-loop turbine control subsystems (also human error) that may create high reference/actual power errors.

B. Power Balance Between Generation and Load

Maintaining good steady state and dynamic load and generation balance is always important. The coupled mode, however, requires the best and fastest power balance to stabilize the Bindura power. In the "isolated mode," exact open-loop power balance improves frequency control.

Songo's single-tuned ac filters are intolerant to significant frequency deviations. Without ac filtering, passive ac loads on the dc busbar must be tripped for protection against HVDC induced harmonic peak voltages. The GMPC's high-gain "disturbance frequency controller"' is designed to help prevent ac filter tripping (see Section II.A). When the filters nevertheless do trip on frequency excursions, the GMPC orders a busbar voltage reduction from the generator exciters to reduce the harmonic peaks.

When system stability demands fast turbine ramping to match generation to a stepped HVDC reduction, all turbines under GMPC control, even those operating against operator-set limits for cavitation control will initially be forced to participate in the ramping. This function is especially important when a tripping of a remote inverter bridge is only detectable as a sudden dc voltage reduction (see Section VI.C). The turbines have two significant cavitation zones that restrict continuous operation. The 50–150-MW range must be passed rapidly while 30-min operation is permitted between 150 and 300 MW, provided that compressed air is available for the alleviation of cavitation.

Due to the relative power ratings, the HVDC's power step for avoiding intermittent current operation during blocking/deblocking of a pole may constitute a problem for the loading of the Bindura line. The GMPC provides a specially smoothed PP0 function (Possible Power to zero) for one or both poles for this purpose. This convenient operator function rapidly ramps away the power of the outgoing pole and utilizes the transient 125% loading capacity of the remaining pole to compensate the final 20% step at pole blocking. On a pole rating of 960 MW, this would amount to a 192 MW step on the steady 500-MW export to Bindura if not carefully controlled. Depending on the initial load, no turbine ramping may be required to take a pole out of operation. It may even be possible to accommodate the final power step without transiently overloading the remaining pole. A similar function (PP0 Release) controls pole deblocking.

Balancing the power generation and load is complicated by the nonideal and time-delayed response of the turbines. Steady-state power of a Francis turbine depends primarily on the gate opening and the water head. It is also influenced by unit's position in the hydraulic circuit. The combined maximum turbine power varies by some 200 MW, depending on the max/min reservoir levels (Fig. 3). However, despite this, each turbine's control has a fixed linearizing curve. Component drift in this old discrete electronic technology circuit and the associated analog communication with the power station makes each turbine's control response prone to individualized gain and offset errors. This results in unequal power sharing with the same GMPC power orders or worst, unexpected "run-away" into overload when offset drifts get amplified by the close-loop gain that depends on the machine's opening.

Turbine power may also vary due to human interference or plant restrictions that are not announced to the GMPC. These factors make it possible to order power above a machine's declared capability and forcing it against this hidden limit when the GMPC strives to reach the higher operator-set limit. Consequently, with matched open-loop parallel power orders to the turbines and the HVDC, only the HVDC would respond; thus raising the load without matching generation. This tends to cause transient frequency deviations or reduced power on the Bindura line.

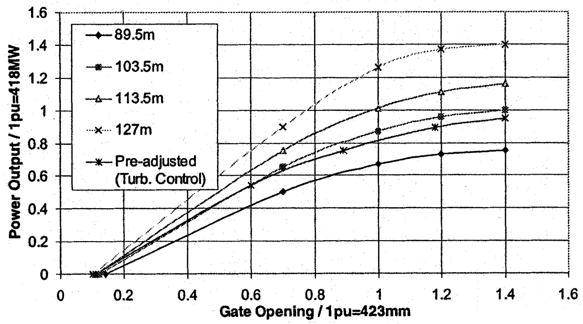

Fig. 3. Turbine power depending on gate opening and water level.

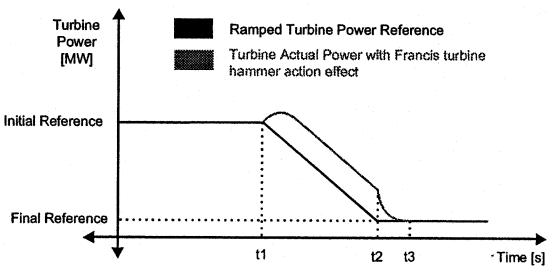

Fig. 4. Water hammer effect during power ramping.

In addition to the above open-loop response errors, dynamic turbine power is also affected by the "water hammer" phenomenon as shown in Fig. 4. A range of special smoothing functions influences power order changes to mitigate this behavior. They act under all conditions to adapt power orders and ramp rates to minimize water hammer effects while controlling for optimum stability and for protecting the hydraulic system against pressure surges.

Particularly during fast turbine ramping, the HVDC power needs to be modulated with calculated compensation to negate the disturbing effect of water hammer power.

Despite the efforts to compensate for these variable characteristics, disturbing open-loop control errors especially in the turbine controls remain inevitable. In the steady-state, these errors are therefore detected and translated into gain, offset, and limit corrections. These R/A controllers must also account for the ever-active governors that add frequency-dependent compensation to the GMPC's orders. If possible, the R/A controllers ensure slow but exact execution of individual steady state orders. For the dc turbines, these controllers provide offset correction below 100 MW. Above 100 MW, the offset errors drive the turbines' very slow gain compensations.

Each busbar also has a R/A controller, ensuring that its group of turbines executes the total busbar order within a small error margin. These proportional controllers act directly on their associated turbine R/A controllers. Although a busbar's R/A controller detects the same transient power errors, while its underlying turbine R/A controllers settle, its main purpose is to counter persistent errors resulting from a turbine running into an unannounced limit. In effect, the busbar controllers compensate the power error (initially absorbed by the HVDC) by raising power on the "healthy" turbines of the particular busbar.

While a busbar R/A controller is adapting, the associated turbine gain controllers are stopped to prevent them from absorbing the temporary offset error as gain errors. Since the busbar R/A controllers act in the proportional mode, the corrections are as fast as the turbine R/A controllers would allow (some tens of seconds) while the turbine gain controllers operate in the 1000-s domain.

C. Protection of AC System Against DC Disturbances

The relative high impedance of the ac link from Cahora Bassa to Eskom makes it susceptible to power oscillations. Disadvantages for coupled operation derive from the impact of large dc power disturbances on the weak ac system. These relatively frequent events result mainly from converter bridge tripping (16 in scheme), inverter commutation faults induced by dips in Eskom's extensive ac system and dc line faults. The latter are primarily due to seasonal fires along the total 2828 km of monopolar dc lines. Because the ratings of the Cahora Bassa machines, bridges and HVDC poles are disproportionately large to the spare ac transmission capability from Cahora Bassa through ZESA to Eskom, a relatively normal event on the HVDC could constitute a major incident for ZESA. In coupled operation, rejected dc load always attempts to escape through ZESA to Eskom. Without timely GMPC action, such sustained flow has the potential of collapsing the ZESA system with undervoltage and overload.

The spare and transient overload capacity of the healthy HVDC pole buffers power rejections of the other pole, and thus, protects the system stability. It attempts to absorb excess power until the turbines have adapted. With insufficient overload capability, the GMPC would rely first on the proposed braking resistors and only second on the busbar splitting criteria. However, in the absence of braking resistors protection depends on the ac/dc busbar isolation criteria. Most important of these criteria are the maximum angle and two excess energy criteria. The energy level for bus splitting depends on whether one or both poles are affected and also on HVDC loading and bridge configuration. The more stringent energy criterion applies for a bipolar current reduction event as typically triggered by inverter commutation failures. Splitting is also triggered if the HVDC system fails to follow one of its pole orders (typically due to transient telecommunication failure during dynamic current control at the inverter). Since coupled busbar operation can only be safely maintained if the GMPC has full control of the HVDC, it is essential to end this mode as soon as such a problem arises. After ac/dc separation, the GMPC controls will deal with the misbehavior in the more robust frequency control mode by shifting load between poles and forcing a power reduction by reducing the nominal dc possible power. The bus-coupler is the default split point but the common busbar mode would require tripping of the Bindura line for splitting.

D. Stabilization of Interconnection After DC Disturbances

During dc disturbances, a portion of the excess energy surges through the ac system and stimulates oscillations in the parallel ac networks. The energy absorbed by the ac network depends on the magnitude of the power surge through the bus coupler and determines the increase in angle between Songo and Apollo. Not only does the loss of dc power import at Apollo cause the Eskom frequency to slow down, but excess power on the Songo busbar also accelerates the Cahora Bassa machines. Both effects contribute to the angle increase. The ac system oscillations are damped by HVDC power modulation ordered by the combined actions of Angle and ZESA power controllers (Section V.A). Since the HVDC recovers in about 100 ms after commutation faults, it is well able to provide some effective modulation power after its recovery. The angle can therefore typically be controlled below the split limit at 125°. With proposed braking resistors to transiently help absorb rejected dc load, system security would be further improved. The energy surge that stimulates oscillations would be reduced and extra modulation power over and above that transmitted by the HVDC would be available.

After splitting the ac and dc systems, the HVDC and braking resistors can no longer affect the stability of the disconnected ac network and the burden to stabilize the ac network reverts to the generator power system stabilizers. The GMPC activates the generator power system stabilizers (PSS) systems of ac generators loaded above 100 MW when it splits the ac and dc busbars.

E. Overload Protection for Bindura

Since the turbine governors remain active even during GMPC control, the 220/330-kV Bindura coupling transformer may be overloaded when the governors increase power in response to ZESA under frequency. The GMPC is designed to maintain the Bindura power order and with its ac turbine R/A control, normally allows only short-term deviations. Additional control is therefore required to prevent Bindura overloading. If Bindura operates separately from the HVDC, its possible power is derived from the maximum possible ac generation (operator-set limits), less the measured uncontrolled ac load (Tete and auxiliaries). If Bindura is coupled to the HVDC with an order greater than 300 MW, Bindura's maximum possible power is determined from its order plus 50-MW margin. A maximum limit of 550 MW is imposed and whenever these limits are exceeded, the turbines are ramped down at 0.5 MW/s. The maximum possible ramp rate of 22 MW/s is reserved for special occasions. That is when a Bindura-Dema line trips or a permanent remote ZESA fault is detected.

If the bus coupler carries power from the ac to the dc busbar when it is tripped, all of the ac busbar generation would be forced down the Bindura line. Under these conditions, the GMPC trips excess generation on the ac bus to avoid overload tripping of the link.

F. Fast Angle Measurement

An essential precondition for the angle control mode is having an intact measurement system as well as fast and reliable communication from Apollo to Songo. Part of the GMPC's angle and frequency measurement equipment, including a GPS clock for telegram synchronization, is situated in Apollo. Relying on the fixed transmission delay of the telecommunication system, GPS-clocked angle information is transferred by dual power line carrier systems (PLC) operating over the HVDC lines and their earth wires. During transient PLC failures, the GMPC reverts for 1 s to an angle estimate before it splits the ac/dc systems. This GPS-based angle measurement for ac system control and damping is the first known application.

G. Automatic Control Mode Changes

The GMPC promotes bus coupler (BC) synchronization by creating slow slipping between the ac systems. Its automatic selection of control mode is essential for realizing robust and safe controls for parallel ac/dc operation. This GMPC control mode selection is based solely on the evaluation of the rate-of-change of angle and is thus independent of status signals from the remote links.

The GMPC automatically changes from "frequency" to "ZESA" mode for the following two cases:

- if the BC is synchronized without the GMPC's interconnection procedure;
- if the BC is in the closed position with the Bindura line disconnected and the Bindura line breaker is closed (local or remote synchronization with ZESA).

On the other hand, if during ZESA mode, the GMPC detects that the HCB/ZESA network has become synchronized with Eskom (i.e., an ac path exists in parallel to the dc link), the GMPC will automatically change over to the required angle control mode.

When in angle mode and one of the isolation criteria is violated, the GMPC opens the split point (usually the bus-coupler) and reverts to the frequency control mode.

When in angle mode, the GMPC will change over to ZESA mode (keeping the bus-coupler closed) for the following conditions:

- GMPC detects that the HCB/ZESA system has become asynchronous with Eskom (e.g., after opening of the remote Matimba line (Eskom-ZESA link);
- violation of negative angle limit (Section IV.D);
- after tripping the Bindura-Dema line (Section IV.E);

IV. ADVANTAGES OF COUPLED OPERATION

A. Full Exploitation of All Generators (See Section I)

B. Security for Remnant AC Load at Bindura (ZESA) Against Generator Trip

In coupled mode, the impact of a generator trip on the ac system is much less than in isolated mode because HVDC power would instantaneously be sacrificed to maintain the ac flow. Furthermore, the standby ac generator (normally operating with low power to avoid cavitation) would be available for generation reserve to both busbars.

In isolated mode, the security of Bindura and other ac loads requires two generators on the ac busbar. This leaves at most three for the dc side. Also after tripping the loaded ac generator, the ac system will experience a transient generation loss while the standby unit ramps to full power in less than 20 s. To achieve this favorable response from the standby machine, the GMPC resets all operator-imposed limits whenever a generator with more than 100-MW trips. The same resetting is applied for the dc generators operating in whatever mode.

Tripping the BC is treated as a generator trip event on both busbars and all turbine limits are reset to 400 MW.

C. Free and Quick Transfer of Equipment

In coupled mode, the GMPC permits free and quick transfer of equipment (particularly generators, Tete lines, and Auxiliaries) between busbars. In particular, this obviates the need for an HVDC shutdown for swapping the only station auxiliary supply between busbars.

D. Enhanced System Performance After Interruption of ZESA-Eskom Link

Although the ZESA-Eskom power flow is not monitored by the GMPC, its actions indirectly depend on the direction of the prefault power flow on that link. Violating the positive maximum angle limit is indicative that ZESA had been exporting power to Eskom at the time of its tripping. Splitting the systems by interrupting the BC flow would therefore be beneficial for ZESA's stability and the GMPC thus trips the BC and reverts to the frequency control mode.

On the other hand, if ZESA were importing power from Eskom, the angle would typically violate its maximum negative value. In this case, the conditions for ZESA would be worsened if the power transfer through the BC would also be interrupted. The GMPC therefore rather keeps the BC closed and changes from angle to ZESA control mode.

E. Protection of ZESA Following the Loss of Bindura-Dema or Dema-Warren Line

The loss of one of these lines with a strong influence on the transfer impedance during isolated mode would most likely also bring about the tripping of the Songo-Bindura line to cause a total blackout of Bindura and Dema.

In angle mode, however, there is a good chance of maintaining the small remaining Bindura/Dema load. Therefore, if the Bindura power suddenly drops from prefault value above 350 MW to below 220 MW while the HVDC has 100-MW continuous spare capacity, the GMPC switches to frequency mode without opening the BC to split the systems. This would be done despite the fact that the maximum angle had been violated. With the BC remaining closed, the surplus ac generation can be partly diverted into transient HVDC overload. As a consequence, tripping of the ac generators and the Bindura and Tete lines (assumed to be on the ac busbar) may be averted. The dynamic overload capability of the HVDC beyond the 100-MW spare capacity combined with the ramping of all turbines contributes to the GMPC's efforts to protect the remaining Bindura and Tete loads.

F. Enhanced Transient Stability for Bindura Single-Phase or Remote Faults

The HVDC power modulation is used to assist the ac system stability during the clearing of single-line-to-ground faults on Bindura as well as remote ZESA faults. With a prefault flow of less than 200 MW, single-phase fault clearing affects only a part of the line's ac load transfer capacity. The GMPC compensates for this loss by rapidly increasing the HVDC's (or braking resistor) orders by an appropriate amount (30% of the Bindura order) for the duration of the fault clearing as indicated to the GMPC by the line protection. The power increase on the HVDC is however limited by its nominal capacity. In frequency mode, a three-phase trip of Songo-Bindura line represents a total load rejection for the ac generators and the loss of the Tete lines that were connected to the ac bus.

G. Prevention of Generator Overfrequency for Bindura Line Trips

In the coupled mode, the ac busbar over frequency resulting from a Bindura trip can be countered more effectively by ramping down all available turbines and also by utilizing the maximum capacity of the HVDC.

H. Enhanced Stability for the DC Bus

Even if the BC has to be opened, the dc bus transiently benefits from coupled operation because many MJ of its excess energy resulting from dc faults, can escape through the ac network to Eskom. Sometimes this energy release might avoid overfrequency tripping of the ac filters.

I. Damping of Parallel AC System

Parallel ac/dc operation offers superior damping of low frequency ac system oscillations that occur after faults or switching in ZESA or Eskom. This is especially important when Bindura operates at high power near the stability limits and while ZESA exports power to Eskom.

V. MEASURED RESPONSES TO DC LINE FAULTS

A. DC Line Fault in Angle Control Without Isolation

The HVDC operates in angle control mode in bipolar operation with two bridges in pole 1 and three bridges in pole 2 at 1200 MW (100% loading). The bus-coupler is closed. Two ac filters and generators 1, 3, 4, and 5 are connected to the dc bus S1. On the ac bus S2, generator 2 (409 MW) is feeding Bindura (411 MW), Tete 1 (4 MW), Tete 2 (21 MW), and the Auxiliaries (8 MW). The BC power is 34 MW from the dc to the ac side. A 160 ms $I_{\mathrm{dref}} = 0$ command is issued for pole 1 (two bridges) to simulate a dc line 1 fault. The energy surge of 95 MJ through the BC remains below the 110-MJ limit and no splitting is required. The GMPC overloads the unaffected pole (Fig. 5). The less than 5% calculated voltage drop at Bindura validates the nonsplitting result. The oscillations of the angle, Matimba, and ZESA powers are well damped after the dc line fault.

B. DC Line Fault in Angle Control With Isolation

Starting with the same prefault conditions as before, a 160 ms $I_{\mathrm{dref}} = 0$ command for pole 2 (three bridges) simulates a dc line 2 fault. The energy surge through the BC exceeds the 110-MJ isolation limit and the systems are split. The GMPC correctly overloads the unaffected pole (Fig. 6). Isolating the ac system from the dc comes early enough to prevent the Bindura voltage dropping below 7.5%. After "clearing" the dc line fault, the ac system is damped by the PSS of the ac generator, which was enabled by the GMPC.

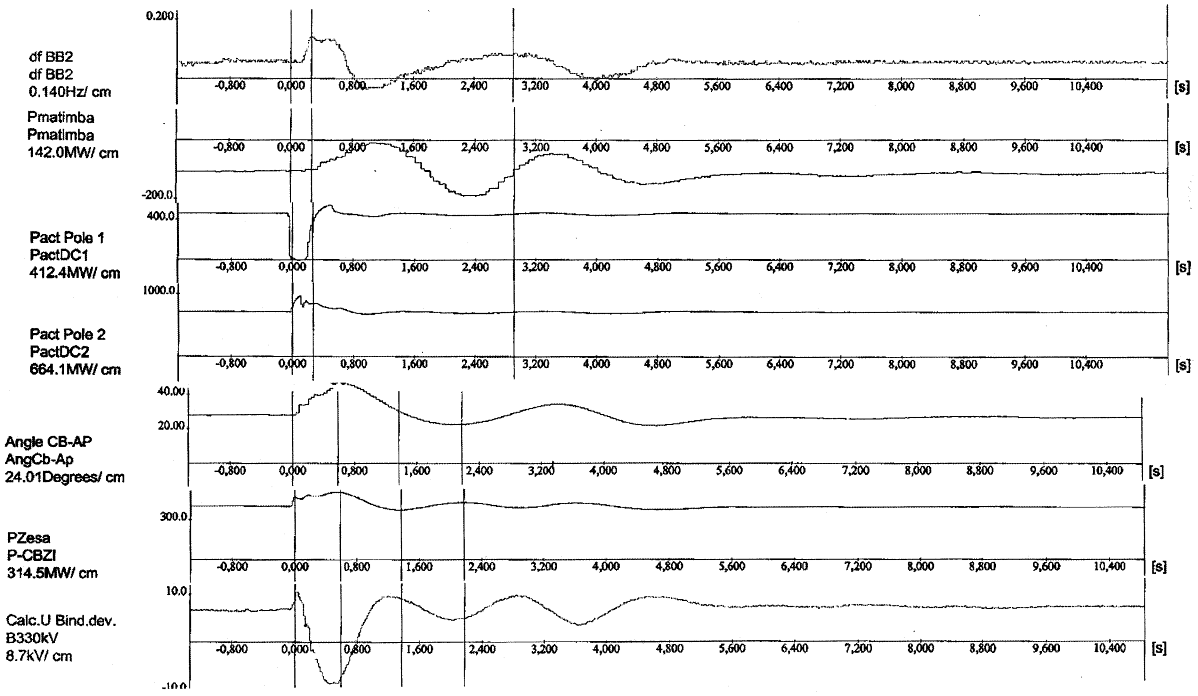

Fig. 5. Test 9.0/2, 30.September 30, 1999, 00:14, dc line fault in angle control (without isolation of bus-coupler).

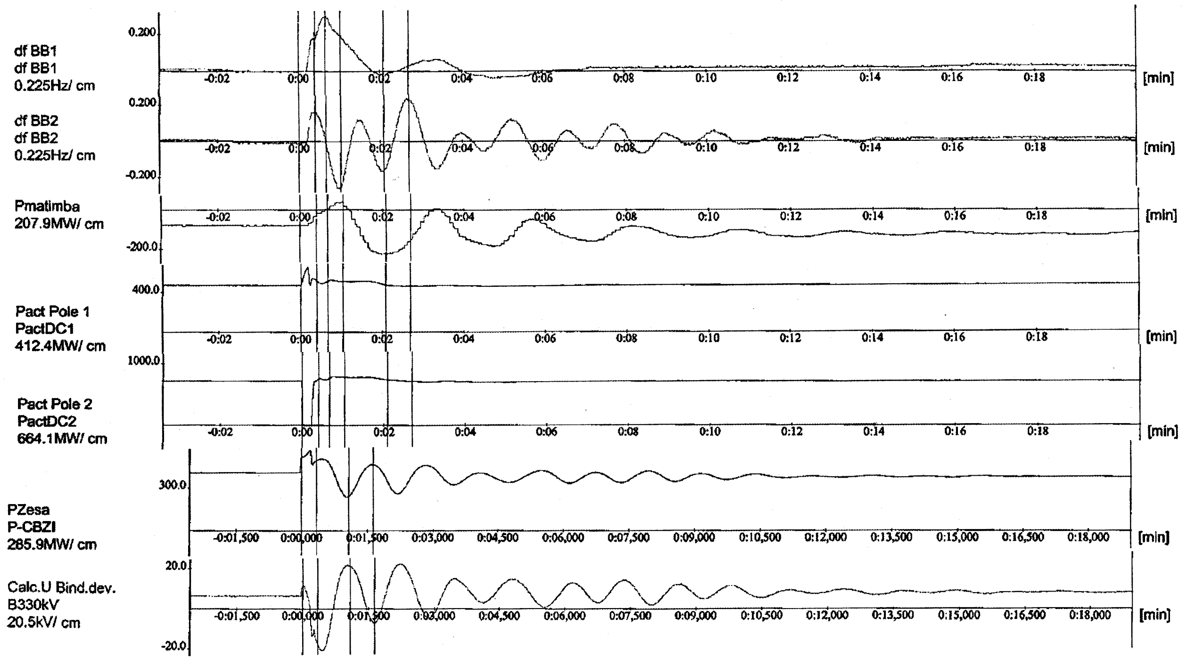

Fig. 6. Test 9.0/3, 30.September 30, 1999, 00:21, dc line fault in angle control (with isolation of bus-coupler).

VI. CONCLUSION

Although optimum exploitation of all machines was the main reason for coupled ac/dc operation, this configuration also offers other important advantages for the interconnected ac system. These are enhanced dynamic stability, transient HVDC support for Bindura single-phase faults, better protection for ZESA against tripping of Cahora Bassa generators, tripping of Bindura-Dema or Dema-Warren lines, and enhanced ac system performance following the interruption of ZESA-Eskom link. Due to the very weak ac system interconnection; the narrow frequency band for the ac filters; the dependency of turbine output on fixed governor precontrol characteristic; the water level and water hammer effects, a new specialized power controller (GMPC) became essential for the successful realization of the parallel ac/dc operation.

Notable features of the GMPC are robust design with minimized external status information, inclusion of controls for future braking resistors, adaptive reference/actual control and supervision of HVDC and turbines to make it robust for all conceivable plant faults, fast GPS-based angle measurement, and automatic control-mode-selection-logic.

Even without the proposed 720-MW braking resistors, the GMPC is capable, through application of various isolation criteria, to realize safe parallel ac/dc operation in which both the ac and dc systems are well protected from disturbances in the other. The main isolation criteria are the maximum angles and two energy criteria. Violations of the positive or negative angle thresholds trigger different GMPC control actions for the purpose of maximizing benefits to the ZESA ac system while also offering best protection to the large Cahora Bassa machines. The energy criteria have been carefully optimized to the HVDC loading and configuration in order to minimize splitting of the ac and dc systems even in the absence of braking resistors.

Since its commissioning in October 1999, the GMPC has preferentially been used (without any modifications!) in its angle control mode, thus efficiently and reliably providing its benefits as described.

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Pieter V. Goosen was born in Brakpan, South Africa, on October 3, 1947. He received the B.Sc. Eng. and B.Sc. Eng. (Hons) degrees in electrical engineering (Elec) from the University of Pretoria, South Africa, in 1970 and 1972, respectively, .

Currently, he focuses on the life cycle management of the HVDC scheme and power transformers of Eskom, Johannesburg, South Africa. Since joining Eskom in 1970, he has been closely involved with the Cahora Bassa HVDC scheme. From 1997 to 1999, he was seconded to Siemens for the GMPC development. He has extensive experience with transformers, capacitors, and SVCs.

Mr. Goosen is a Cigré SC12 member and Special Reporter.

Peter Riedel was born in Herten/Recklinghausen, Germany, on July 20, 1962. He received the Dipl.-Ing. and Ph.D. degrees in electrical engineering from the University of Hannover, Germany, in 1989 and 1994, respectively.

Currently, he is with SIEMENS AG, Erlangen, Germany, where he has been since 1997. Before, he was a Consultant with FICHTNER, Stuttgart, Germany, in the area of ac and HVDC power systems. His main activities include basic design and system studies for HVDC systems.

John W. Strauss was born in Johannesburg, South Africa, on May 10, 1968. He received the B.-Ing. degree in electronic engineering from the University of Pretoria, South Africa, in 1994.

Currently, his main activities comprises engineering and commissioning of HVDC transmission systems. His previous experience includes automization and drives control for the steel, paper, and gold mining industries.