LEYTE-LUZON HVDC POWER TRANSMISSION: COMMISSIONING HIGHLIGHTS, PERFORMANCE MEASUREMENTS AND OPERATING EXPERIENCE

by

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Abstract - *The Leyte-Luzon HVDC power transmission system has achieved a converter availability of 98% during its first 15 months of commercial operation.*

Despite AC network constraints the commissioning tests were able to optimise the controls and demonstrate the effectiveness of the special frequency and emergency power controls in stabilising both the Leyte and Luzon networks. The performance measurements confirmed that the specification requirements have been met with no appreciable level of interference.

Keywords - HVDC - Control - Interconnection - Commissioning - System test - Geothermal generation - Availability - Utilisation – Disturbance

1. INTRODUCTION

The 440 MW Leyte-Luzon HVDC Transmission Project connects the power system of Luzon, the major island of the Philippines and includes the capital, Manila, to that of Leyte which is part of the Visayan island group. This project is part of National Power Corporation's (Napocor) overall plan to connect the existing Luzon, Visayas, and Mindanao grids into a single national grid (Figure 1) [1].

The demand for electrical energy is increasing rapidly in the Philippines and the Leyte-Luzon interconnection makes it possible to transmit environmentally friendly geothermal energy to the Manila area. It is also a vital part of Napocor´s development program as it permits a more efficient balance of energy supply and demand.

This is the first time a HVDC system has been connected to a network almost completely supplied by geothermal power and is by far the largest load on the Leyte system - about 2/3 of the installed capacity. It also represents the largest power source on the island of Luzon and, as this power has to be transmitted from Naga in the south-east some 250 km to Manila, the effects on the Luzon grid are considerable.

This paper describes some of the special control features which are necessary to ensure the stability of the Visayas and Luzon power systems and to allow the geothermal power plants to be operated at maximum efficiency. The results of several tests of these special control functions carried out during commissioning are presented as well as a brief discussion on equipment related problems and initial operating experience.

Figure 1 - Leyte-Luzon HVDC transmission project

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It is considered that the thorough testing contributed to the excellent performance of the HVDC system during its first full year of operation - the converter availability has exceeded the guaranteed value of 98%, and high availability is expected in the future.

2. GENERAL SYSTEM DESCRIPTION

The Ormoc converter station is located on Leyte, one of the islands of the Visayas group, and acts normally as a rectifier. The five major islands of this group are connected by AC lines and undersea cables at 230 or 138 kV. Cebu has the largest load and mainly fossil fuel fired conventional thermal generation, it imports power from geothermal and thermal resources on Negros and Panay and up to 200 MW from Leyte. Leyte is also connected to Samar, and these two islands (Leysam) have a load between about 70 MW and 120 MW.

As shown on Figure 2, the geothermal generation on Leyte has a rated capacity of just over 700 MW. With all units available the firm capability is about 665 MW. A 30 MW stand-by gas turbine was available during commissioning of the HVDC system.

The Naga converter station is located in the south-east corner of the island of Luzon and acts principally as an inverter. As shown on Figure 3, it is connected to the 500 kV double circuit Naga-Tayabas (operating at 230 kV) and Naga-Labo transmission lines (and thence to the Manila area). These lines also transmit power from the Tiwi and Bacman geothermal plants.

The Leyte-Luzon HVDC interconnection is monopolar as shown in Figure 4. The converter valves, smoothing reactors (240 mH) and converter transformers are the same design at both stations. The three 35 Mvar filter banks at Ormoc are identical while, at Naga, there are two identical 70 Mvar banks and a 78 Mvar high pass filter. The AC filter circuit breakers are equipped with synchronous closing devices. A passive DC filter (12th and 24HP) is also installed at each converter station.

Shore electrodes made of 40 vertical sub-electrodes are connected by overhead electrode lines. As the HVDC line is bipolar, three operating modes are possible, the first one being preferred for its lowest losses:

- two HV conductors in parallel with sea return
- one HV conductor with sea return
- metallic return.

3. MAIN CONTROL FUNCTIONS

The Leyte–Luzon HVDC transmission system normally operates in power control mode (Figure 5). Current control can be used as a back-up mode. A back-up synchronous control is automatically activated in the event of loss of telecommunication. In this mode the current response is used as the inverter current order, so assuring that the current margin is always maintained. In addition, the reduced voltage (80%) operating mode can be ordered by the operator as well as being applied automatically after repeated line faults.

To avoid Leyte system collapse should generation be reduced, the HVDC link is normally operated in Leyte frequency control mode. This is the principal control mode of the Leyte-Luzon HVDC system. The frequency controller (FC) is a proportional regulator with a pre-set dead band.

Both converter stations have reactive power controls (RPC) which maintain the reactive power balance with the networks and determine when to switch filters. The

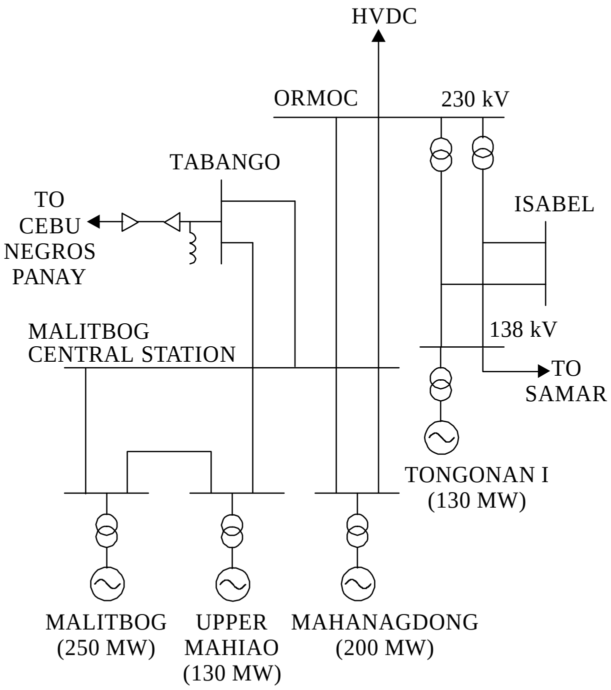

Figure 2 - AC system around Ormoc

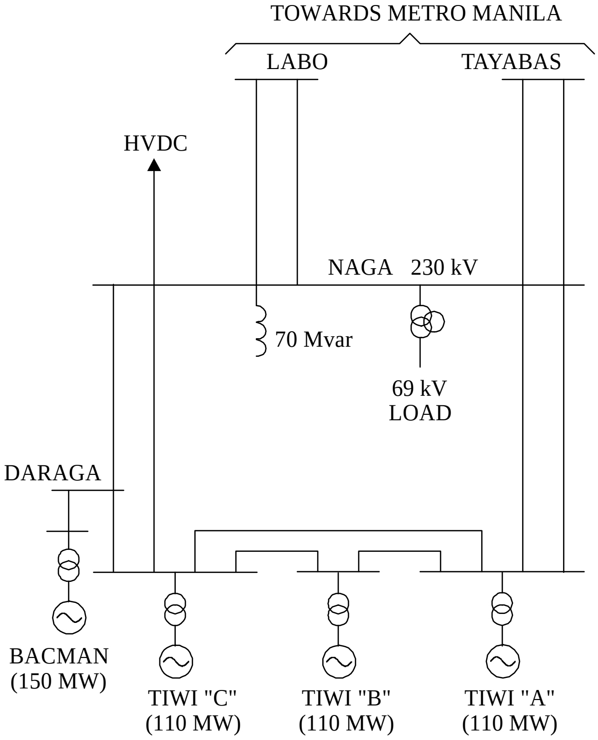

Figure 3 - AC system around Naga

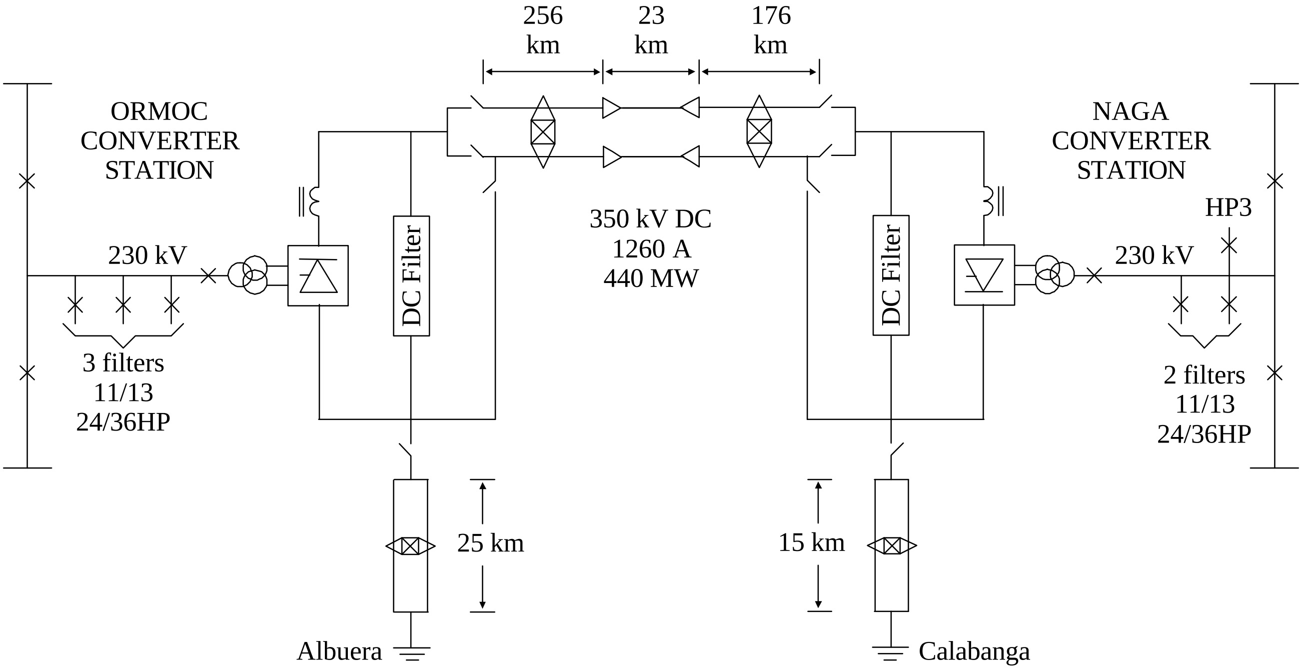

Figure 4 - Schematic of the HVDC interconnection

RPC is provided with a step voltage (flicker) controller to minimise voltage steps on filter switching, described in section 5.6. The net reactive power balance can be set by the operator and the RPC also ensures that sufficient harmonic filtering is always connected.

To avoid overloading transmission lines on Luzon, five emergency power control modules (EPC) modulate or limit the transmitted power based on the status of the transmission lines or system frequency. These are described in Section 5.5.

The Line Fault Locator (LFL) covers the total distance between the two converter stations and quickly informs the operator on which of the two DC line conductors the fault occurred as well as the distance to the fault.

4. GEOTHERMAL GENERATION

Geothermal power plants use the heat in high quantities of relatively low quality naturally occurring steam to produce high pressure and temperature steam to drive a conventional steam turbine. The raw steam is collected from wells located over a fairly wide area, referred to as a steam field. The geothermal power producers on Leyte request up to 24 hours notice of the need to open or shut a given steam field. Once open, a steam field takes up to 4 hours to achieve full capacity.

The rate of change of power from a set of generators is also limited. During the commissioning of the HVDC system it was generally attempted to limit this to about 200 MW/h. Power order ramp rates of 20 MW/min could be followed by the geothermal plant operators if the total change was limited to about 100 MW. Rapid power reduction in an emergency can be achieved by releasing high pressure steam to the atmosphere and, after such an action, power can be increased at a fairly fast rate since the steam is available.

Due to the relatively long steam side time constants the HVDC system is usually operated in Leyte frequency control mode so that sudden loss of generation capacity or reduction in local load (eg loss of the cable to Cebu) is immediately compensated for by a change in HVDC power transmission. This allows the Visayas system to be run with virtually zero spinning reserve and limits the probability of having to vent steam.

Frequency control cannot prevent sudden reduction in HVDC transmitted power (due to blocking, EPC action, etc.) which results in significant acceleration of the Leyte generators. A sequence of generator tripping based on frequency was developed to ensure that only the minimum amount of generation needed to preserve stability is tripped. Planned and inadvertent blocking from 440 MW did occur during commissioning and did result in tripping of some Leyte generators, however the units which were tripped were sufficient to stabilise the frequency without causing loss of any of the major generators or other system load.

5. TRANSMISSION TESTS

5.1 General Aspects

The transmission tests were performed in two stages between March and August, 1998. All basic control and protection functions were verified at lower power to reduce the impact on the AC systems. Clearly it was also necessary to verify the performance of the HVDC system at rated power which involved both deliberate and unintended blocking from 440 MW.

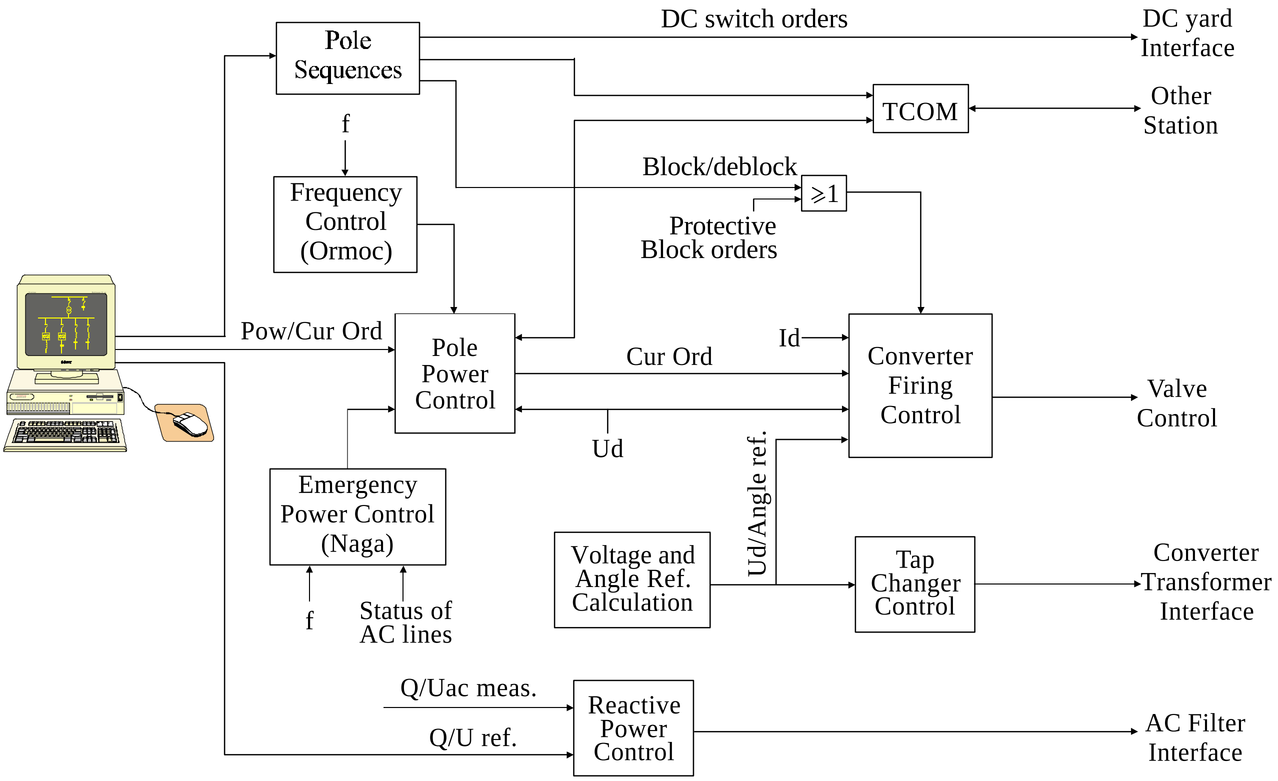

Figure 5 - Simplified block diagram of the converter controls

Network constraints, official holidays and an election period extended the total commissioning duration since testing could not be performed continuously. Problems with the Leyte-Cebu AC interconnection forced some of the testing to be done with the HVDC system islanded on the Leyte system. In this configuration the number of connected geothermal machines and the Leyte network voltage were critical, particularly during de-blocking and until a sufficient power level was reached.

The non-availability of the Naga reactor and the Naga-Tayabas transmission lines imposed operating restrictions and contributed to delays in the commissioning; however the fact that the HVDC system was able to function well with the reduced AC system capabilities is significant.

5.2 Control Instabilities

At the beginning of high power testing an oscillation in the DC quantities at about 97 Hz was noted which had not been seen during low power testing. It was found that a software error had caused a normally temporary high value of the gain of the current control amplifier to be present continuously. This was corrected easily by a change in the software logic.

5.3 Operation with 5% Minimum Current

An important feature of the Leyte-Luzon HVDC system is that it is designed to operate continuously at 5% of rated current. This minimises the disturbance to the AC networks during start/stop and is particularly needed when the Leyte system is islanded. The valve design was shown to be able to maintain this level without discontinuous current. The converters can, however, be exposed to more frequent operation with discontinuous current during AC voltage reductions at the rectifier due to remote faults with long clearing times or transformer energisation. Protective functions (such as valve misfire protection) which could mis-operate during such events had to be tested to ensure correct performance.

5.4 Frequency Control in Leyte

To make full use of the Leyte geothermal resources the Visayas system is operated with virtually zero spinning reserve. The HVDC power transmitted to Luzon must be reduced if significant Leyte generation is lost.

The Frequency Controller (FC) was deactivated during the first set of commissioning tests in order to test all the basic control functions. However, the FC was active during the major part of the testing period and so was exposed to many different disturbances and operator actions, e.g. power ramping, start/stop, control mode changes, DC line faults (figure 9), and AC system disturbances on both Leyte and Luzon sides.

Several tests were performed to verify the performance of the Frequency Control, including trips of complete geothermal plants. Tests were performed both with and without telecommunication in service. In all tests the FC acted correctly to change the transmitted power and bring the Leyte network frequency back close to 60 Hz.

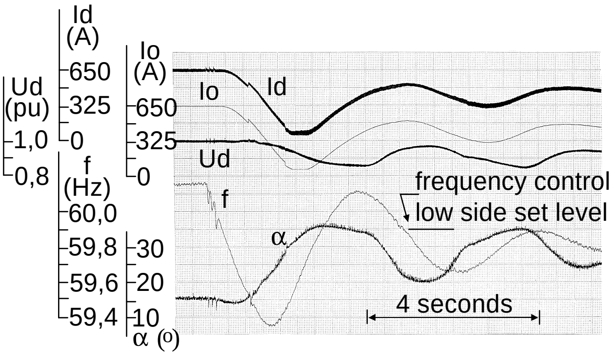

Figure 6 - Load rejection test at Mahanagdong

For reference, a plot of the HVDC quantities and system frequency against time is shown as Figure 6 for the case of a 158MW load rejection at Mahanagdong.

5.5 Emergency Power Control

The Emergency Power Controller (EPC) reduces the transmitted power to help the Luzon AC network. The EPC over-rides Leyte frequency control and consists of five power reductions which are imposed automatically if specific system conditions are encountered (Table I). The first one is always active while the other four can be individually activated by the operator.

Table I – Description of the EPC functions

EPC	Initiated by	Action
1	Loss of both Naga-Tayabas lines	Block DC link
2	Loss of one Naga-Tayabas line	Reduce power to 440 MW at 15 MW/s
3	Loss of both Naga-Labo lines	Reduce power to 80% of prefault at 1000 MW/s
4	Loss of telecommunication	Reduce power to 440 MW at 15 MW/s
5	Luzon frequency > 60,6 Hz	Reduce power until f < 60,3 Hz

To detect if an AC line is not available the EPC system uses either breaker status or line power measurement. Special care has to be taken when using measurement of line power to prevent inadvertent initiation of the EPC during power swings.

The tests of the EPC activation modules were initially performed by simulating the status of the breakers of the critical AC lines or the power measurement on the AC line. Later "natural" events occured which led to EPC actions. Figure 7 shows the initiation of EPC 3 after an AC fault resulted in the loss of both Labo lines.

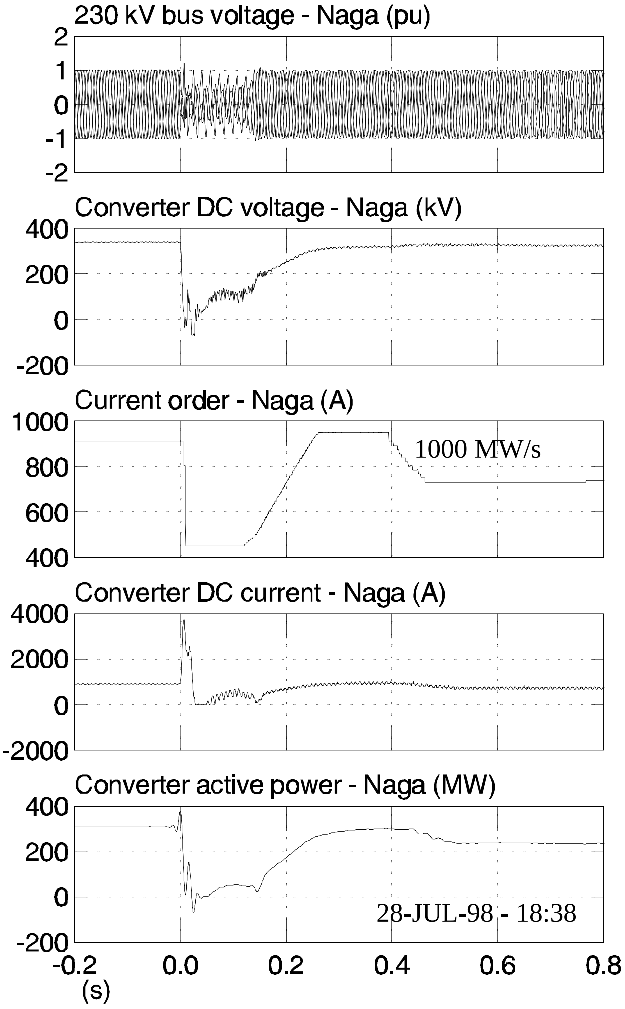

Figure 7 - AC faults on Labo lines and EPC 3

5.6 Step Voltage Control

Reduction of the voltage step when switching a filter at an inverter has been implemented on previous projects (appendix 8.2 of [2]). As control actions are only taken at the inverter this is relatively simple and is effected by temporarily increasing the extinction angle at the instant of filter breaker closing to increase the reactive power consumption. The extinction angle is later ramped back to normal over a few seconds. Prior to switching a filter off, the extinction angle is slowly increased and is then stepped back to normal as the breaker opens. During the sequence the active power is held relatively constant by a fast controller. This function is installed at Naga and tests showed that the voltage step is reduced from 4% to 3% without much of a transient at the rectifier. If needed, the voltage step could probably be reduced further.

For Leyte-Luzon, a similar function was also added at the rectifier. This requires co-ordination of actions with the inverter since, at filter switch in, the angle has to be increased simultaneously at both ends at the instant the breaker is closed and then ramped back slowly. At filter switch off, both angles have to be increased slowly and stepped back at the instant of the breaker opening. This control reduces the step voltage from 1,2 to 0,6% at the rectifier; but causes a 1% voltage step at the inverter, as shown in Figure 8. This must be considered when evaluating the efficacy of such a function at a rectifier.

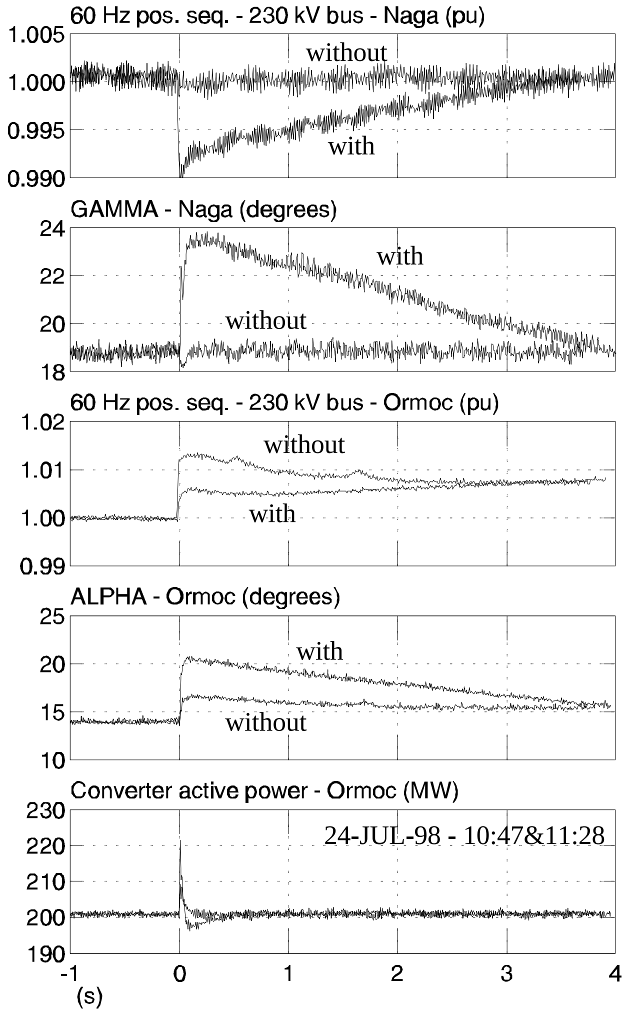

Figure 8 - Filter closing in Ormoc with and and without step voltage control

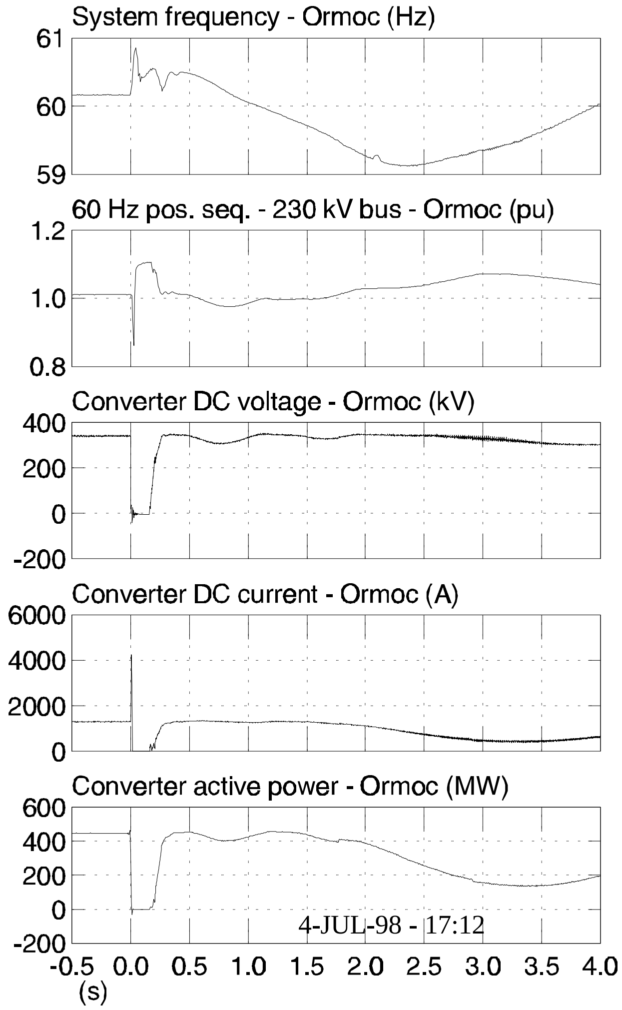

Figure 9 - Staged DC line fault at Ormoc end

5.7 DC Line Fault Locator

The fault locator evaluates the distance to a fault using the travelling waves originating from the fault to stop GPS synchronised clocks installed in Naga and Ormoc. The design used on previous projects had to be adapted for Leyte-Luzon to allow for the presence of a cable in the middle of the line. For Leyte-Luzon, the signal to stop the GPS clock is taken from a special winding on the DC line current transducers (DCCT) rather than by a current signal obtained from a capacitor installed on the DC line as used in some previous projects.

Twenty seven (27) DC line faults were staged for the evaluation of protective functions and the fault locator. Faults were applied between the line conductor and the tower using a pendulum made with fuse wire at five locations at various power levels and operating modes.

Figure 9 presents typical results of such a test: this fault, as it was close to the rectifier, was sensed by the derivative part of the line protection which initiated a fast retard to extinguish the fault. After a de-ionisation time of about 150 ms the re-start was successful. This event shows a significant frequency excursion: at first, the frequency increases to about 60,5 Hz during the de-ionisation but an under-swing (59,1 Hz) follows about two seconds later. The magnitude of the under-swing is interesting as there was no loss of generation during the event. It seems that the turbine governors reduced steam input quickly but were slow in restoring it again.

The fault locator proved to be very precise for staged faults - evaluating the distance of the fault to within a span; however it was not so successful with faults due to vegetation. Figure 10 is an example of such an event with three successive faults occurring on the Leyte side (deduced from the rate of change of DC line voltages recorded in Naga and Ormoc). The top two curves show that the first two faults were detected by the derivative part of the line protection while the third was detected by the level part. It also shows the third restart was at reduced voltage. The three bottom curves are a zoom of the third fault and show that the steady state impedance of the fault was about 160 ohms.

For this type of fault the line voltage does not collapse entirely at the instant of fault. The transient is enough to stop the GPS clock at one end but is too attenuated at the other end, thus preventing a distance evaluation. After commissioning enhancements were made to the LFL which improved its performance significantly. However it still does not locate all vegetation related faults.

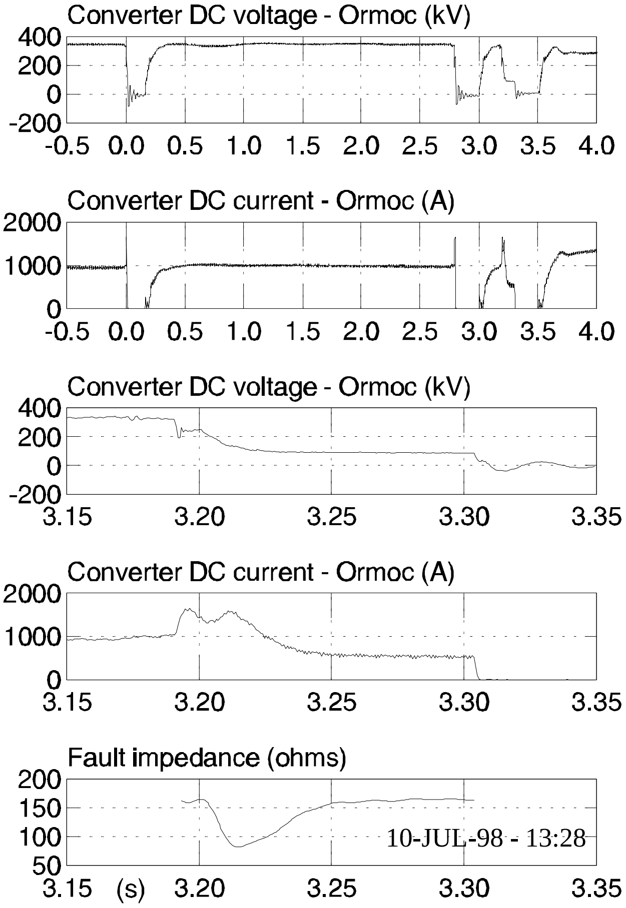

Figure 10 - Vegetation induced DC line faults

5.8 AC System Disturbances

On Leyte, a number of planned AC system disturbance tests were performed including generator tripping, AC line faults, and load shedding as discussed previously. On Luzon, the critical state of the AC system precluded staged tests, however a number of AC line faults did occur naturally (e.g. lightning) and the response of the DC link was recorded and analysed. Cases both with and without commutation failure were observed and the recovery was normal (as in Figure 7). It was noted that the DC link sensed the perturbation for fairly remote faults in the Metro Manila area, but the response was very stable.

Another observation was that, on Luzon with only one Naga-Tayabas line in service, the negative sequence voltage (V2/V1) increased significantly as the HVDC transmitted power rose - from 0,9% at 22 MW to 2,7% at 440 MW. This did lead to some generator tripping in southern Luzon. Since the transmission lines are not transposed, the voltage unbalance increases as the power transmitted towards Metro Manila rises from around 200 MW to over 600 MW. The presence of the second Naga-Tayabas line improved the situation, and some help was obtained by changing conductor positions on some double circuit lines.

On Leyte, an over-sensitive relay is believed to have tripped the newly commissioned cable to Cebu after a by-pass pair operated at Naga (the relay was modified). The high generation to load ratio results in a high X/R value and a tendency to resonance at around 5th to 7th harmonic. This resonance was evidenced when closing a generator transformer breaker not equipped with pre-insertion resistors tripped the HVDC transmission. All DC converter transformer breakers are fitted with pre-insertion resistors, so no similar problem was noted.

6. PERFORMANCE MEASUREMENTS

Tests were performed during commissioning to verify AC and DC filter performance, conducted and radiated noise, audible noise, and the electrode parameters.

6.1 AC Filter Performance

A maximum value of 1% was specified for individual voltage harmonics. In Ormoc, this figure was exceeded at the 7th harmonic at one stage but, when the test was repeated to investigate this, the high level had vanished and was not experienced again. A specific combination of power plants and AC system configuration is thought to have created a resonance, but this was never proved. At Naga, a high level of 3rd harmonic was found; but this was related to the high level of voltage unbalance.

6.2 DC Filter Performance

A maximum value of 2,0A was specified for equivalent psophometric current (I_{PE}) when operating with normal AC voltage (between 219 and 242 kV). This value was only exceeded when operating at minimum current and reduced voltage, a very rare condition.

6.3 Conducted and Radiated Noise

The maximum value of 14 mV (4 kHz bandwidth) in the power line carrier (PLC) band (75kHz to 500 kHz) specified for the conducted noise was not exceeded. The radiated noise was also found satisfactory as it did not exceed the specified level (100 mV/m at 500 kHz).

6.4 Audible Noise

The highest outdoor sound level at a distance of 200 m from the HVDC equipment was measured at 56 dB(A), which was 10 dB(A) below the specified maximum.

6.5 Electrode Parameters

The measured values of voltage gradient on the shore and in the water were much below the specified levels of 5 and 1 V/m respectively. The current balance in the sub-electrodes at Albuera is not yet as close as desired.

7. EQUIPMENT PROBLEMS AND SOLUTIONS

During the commissioning one converter transformer failed in operation and a large number of thyristor valve grading resistors failed. The transformer was repaired in Sweden and the grading resistors were replaced on site by resistors from another supplier.

The most probable cause for the fault on the converter transformer has been identified positively enough to be able to say that the fault is not of a generic nature.

The resistor problem was traced to cracks in the epoxy insulation and resistors of a new type were installed.

8. OPERATING EXPERIENCE

The converter energy availability (EA) for the first 15 months of commercial operation has been 98,11%. The energy availability of the whole interconnection was 0,8% lower because of the time used to cut trees under the DC line. The guaranteed converter availability of 98% was attained in the first year of operation.

The utilisation factor of the interconnection in the first year of commercial operation was limited to about 80% due to restrictions in the amount of power available for export to Luzon. This limitation abated in the following three months and the utilisation factor has reached 90%.

DC overhead line to ground faults have been the main cause of forced outages. These faults are caused by fast growing vegetation underneath the DC line. Clearing of the right of way is therefore important to reduce the number of forced outages.

9. CONCLUSION

The Leyte-Luzon HVDC Power Transmission system was successfully commissioned and started commercial operation in August 1998. Further optimisation of the DC line fault locator might enable it to locate all faults due to vegetation. The step voltage control has shown its ability to reduce step voltage on filter switching by half at Ormoc but causes a 1% voltage step at Naga. At Naga, it reduces the step voltage from 4% to 3%.

Simultaneous commissioning of the HVDC system and geothermal plants in Leyte presented challenges, but commissioning went relatively smoothly. Converter frequency control in Ormoc demonstrated the ability of the HVDC link to modulate power to ensure stability of the Visayas network and limit tripping of generators at the Leyte geothermal plants. Emergency converter control actions in Naga have effectively minimised the impact of loss of lines in the Luzon network.

Performance measurements have shown the converters to have no important impact on the connected networks and on the environment.

The prompt intervention of NAPOCOR operation and maintenance personnel combined with well planned and quickly performed annual maintenance have permitted the converters to attain the guaranteed availability of 98% in the first year of operation.The utilisation factor was reaching 90% in the fall of 1999.

10. ACKNOWLEDGEMENTS

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11. REFERENCES

[1] Fidel S. Correa, Leif R. Wilhelmsson, Jacques F. Allaire, "Leyte-Luzon HVDC Power Transmission Project", [Proc. CIGRE Symposium on Power System Issues in Rapidly Industrialising Countries, Paper 210-04, Kuala Lumpur, Sep.1999]

[2] "Guide to the Specification and Design Evaluation of AC Filters for HVDC Systems", [CIGRE Brochure n^{o} 139, Working Group 14.30, Apr.1999]