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Automatic control for a Hvdc transmission scheme

Francocci, Enrico

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controller and a further deviation angle caused by Δ_i.

That means: β max + ($\mathcal{E}_1'$ min + Δ_i)

Equation (i) is only valid up to the limit $\mathcal{E}_1'$ max (= - 1,7 V), because as stated previously, the γ control system is replaced, by the open loop Id controller, if $\mathcal{E}_1'$ max is not limited.

Thus as the voltage control output is blocked to $\mathcal{E}_1'$ max and $\mathcal{E}_1'$ min through potentiometer settings, two other potentiometers are also used at the voltage control output to stop possible increasing or decreasing of the firing angle β beyond angle 85° and 30° respectively on the variation of the error function $\mathcal{E}_f$, when direct line disturbances occur.

4.3.3 Generation and Synchronization of the Firing Pulses

The generation of the firing pulses is carried out by a stabilized generator which converts a train of 300 Hz ramp pulses from a primary generator into a train of 300 Hz rectangular pulses. (Fig. 4.10, 4.11). Since the primary 300 Hz ramp generator is synchronized with the AC network the new rectangular pulses will also be synchronized with the (Escom) network. The synchronization allows the firing pulses to be conveyed to the valve gates with an advance angle β which, as proportional to the voltage control function $\mathcal{E}_f$, represents the actual firing angle, computed by the real time processor. (See paragraph 4.2).

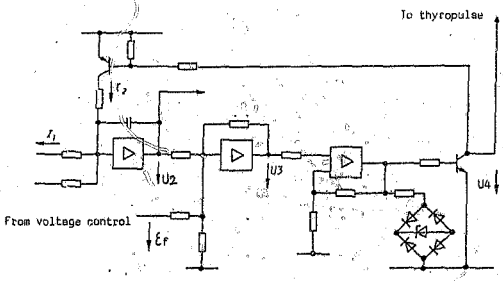


Fig. 4.10 Basic circuit diagram of the pulse generator.

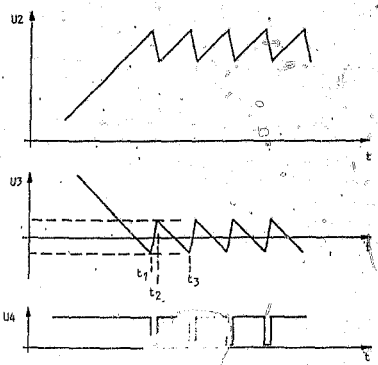


Fig. 4.11 Time diagram of the pulse generator with $\varepsilon_r = 0$ (Zemco *TSE*, 1979).

The firing pulse generator is followed by a 6 pulse ring converter (Fig. 4.12) which re-shapes the pulses and allocates each to one of the 6 paths (see paragraph 4.3.4) used for the transfer of the firing pulses to the valve gates. In this manner the 6 bridge valves are fired in the required sequence and with the proper advanced angle β in relation to the voltage across them.

(a) Synchronization and firing levels

The synchronization of the firing pulses with the AC system is obtained by clamping the 300 Hz ramp pulses at the network line-to-line replica period.

In other words each firing pulse from the generator is made coincident in time with the positive to negative reversing point of the line-to-line voltage, which is present across the valve when the firing should occur.

The 300 Hz pulses are therefore synchronized with the AC system voltage only when the bridge is ready to be switched on, that is, busbar links closed.* Moreover it must be emphasised that as the firing angle range for an inverter of Apollo is in vary from 85° to 30° the synchronized pulses are always shifted by the real time processor into the aforementioned angle range.

* The synchronizing voltages are detected by the voltage transformers located between the busbar links and the bridge breaker.

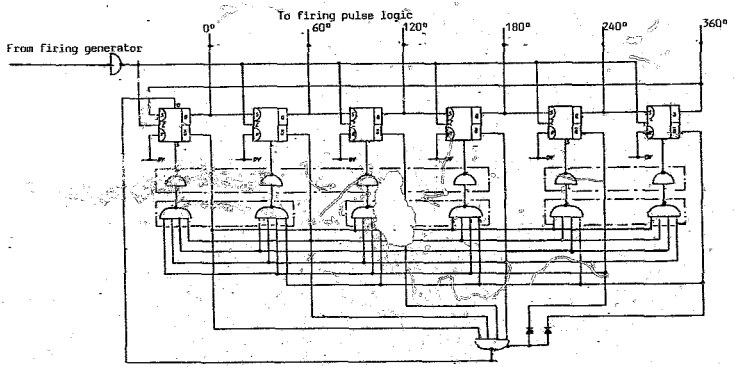


Fig. 4.12 Thyropulse or ring counter (Zamco TSE, 1979).

For instance when the bridge is ready to be switched on, the output of the 90° rate of change circuit will add a firing level (5 V) to the 300 Hz ramp generator output (see Fig. 4.11). Such a firing level moves the synchronized pulses to the 90° degree value firing angle since the bridge is out of operation and the pulses are prevented from reaching the valves.

When the bridge is switched on, the firing level will decrease from the 90° firing angle as the firing angle is brought to its minimum by the processors. The firing levels are determined at any instant by the varying value of the voltage control function $\mathcal{E}_f$.

(b) Pulses Generator and Firing Pulse Shifting

The basic circuit of the 300 Hz generator is given in Fig. 4.10. As stated in paragraph 4.3.3(a), the valve firing pulses are synchronized with the AC system when the bridge is ready to be switched on. This situation is clearly presented by the response signals of the pulse generator during the interval at which $\mathcal{E}_f = 0$. At instant t_o $\mathcal{E}_f$ changes value and causes the pulse angle shifting indicated in Fig. 4.13 as $\Delta\beta$ (Zamco TSE, 1979b).

4.3.4 The Firing Pulse and the By-pass Logic

Two logic circuits identical to the one shown in Fig. 4.14 provide the paths to the firing pulses to the positive and negative bridge valves respectively.* The selection of the firing pulses to be sent to

* NOTE: Refer to Fig. 4.17. The positive and negative bridge valves are represented in commutating group I and II respectively.

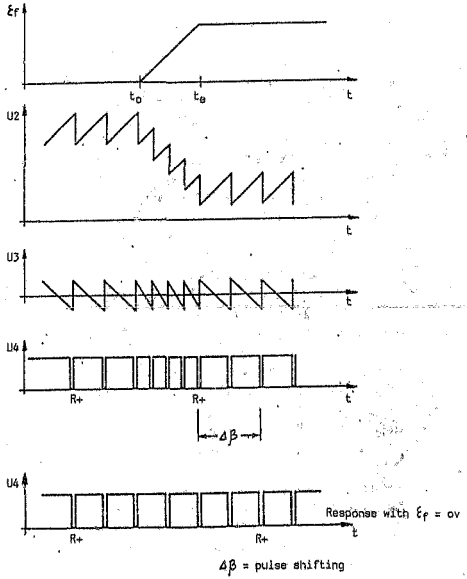


Fig. 4.13 Response of the pulse generator by input control voltage $\varepsilon_f = f(t)$. (Zamco TSE, 1979).

the valves is consistent with the actual electrical condition of the bridge. In the steady state therefore, the firing pulse logic allows only the passage of the firing pulses controlled by the γ extinction angle regulator or the inverter current controller. During the transients the pulses from the by-pass generator (see paragraph 4.5) are logically selected to fire the available pair of bridge valves* to by-pass the DC system current during the opening of the by-pass breaker, and thus to preserve it from damaging flashovers (see paragraph 4.5).

The by-pass logic (Fig. 4.14) generates the pulse $\Delta\varepsilon_f$, (see paragraph 4.5), which limits the end of the bridge switching-on transient and the start (90° firing) of its normal operation. (30° firing).

During the bridge switching-off, the by-pass logic provides the pulses from the 100 Hz generator** to the 6 firing paths of the firing logic to by-pass the DC current through the valves on the closing of the by-pass breaker (see paragraph 4.5).

On the occurrence of valve commutation failure (see Chapter 5) the normal firing pulses from the pulse generator are blocked to allow the free passage of the protecting intercept and set pulses generated by the commutation failure detector.

Finally the firing pulse logic transmits a start and a stop pulse to the outdoor control circuit. These two pulses are formed by splitting the originary firing pulse. (The stop pulse is transmitted 6,6 ms after the start pulse). (see Fig. 4.15).

* for instance R+ and R-

** the valve pair is kept conducting during by-pass operations by firing it with a 100 Hz pulses

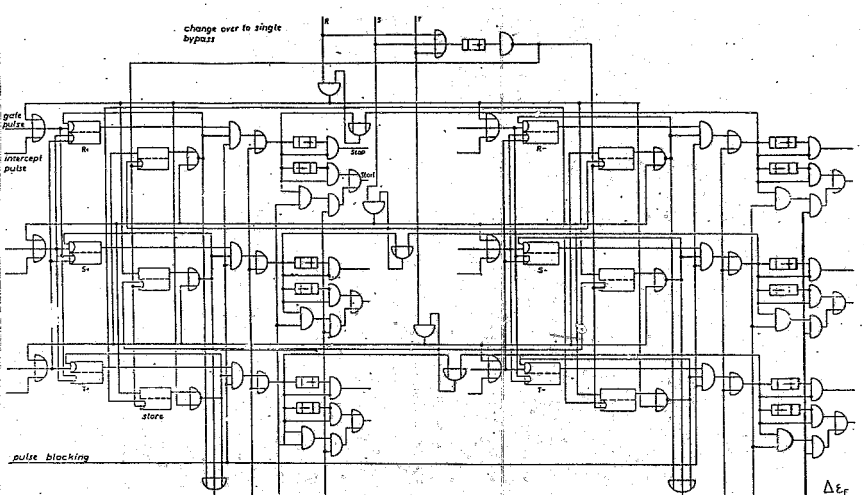


Fig. 4.14 Pulse firing and by-pass logic.
(Zamco TSE, 1979).

4.3.5 *Transducer or γ Control Loop Feed-back*

The schematic diagram of Fig. 4.15 shows the feed-back block of the γ extinction angle control (transducer) loop.

The feed-back circuit performs the following functions:

(a) measurement of the γ angle of each valve during a commutation cycle

(b) conversion of the 6 individual γ extinction angles into proportional voltages

(c) storage of the 6 γ angle converted voltages in the memory

(d) selection of the minimum voltage converted to form the γ actual at the input of the γ controller (paragraph 4.3.2).

Measurement and conversion of the γ angles are carried out by two integrators symmetrically located on the transducer circuit so as to receive and measure only the γ pulses related to the superior and the inferior commutating groups* of valves respectively (signal U_8 and U_9 in Fig. 4.15 and 4.16. The γ pulses (U_8 and U_9) are passed by a OR gate which collects the 120° shaped γ pulses from the bistable flip-flops A, B and C. Since the interval between the current and voltage pulses corresponds to the extinction angle of the respective valve, the γ pulses are formed in conjunction with the setting and resetting of the aforementioned bistable

* For the superior and inferior commutating groups refer to Fig. 4.17.

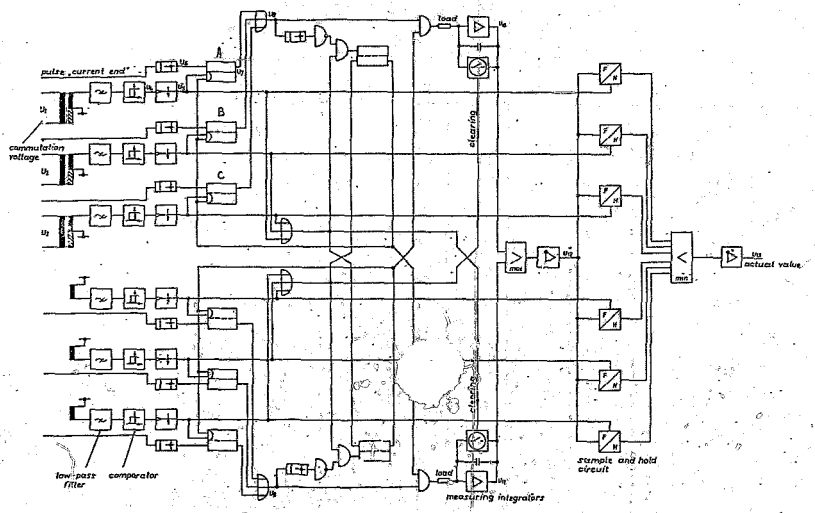


Fig. 4.15 Control loop feedback circuit. (Zamco TSE, 1979).

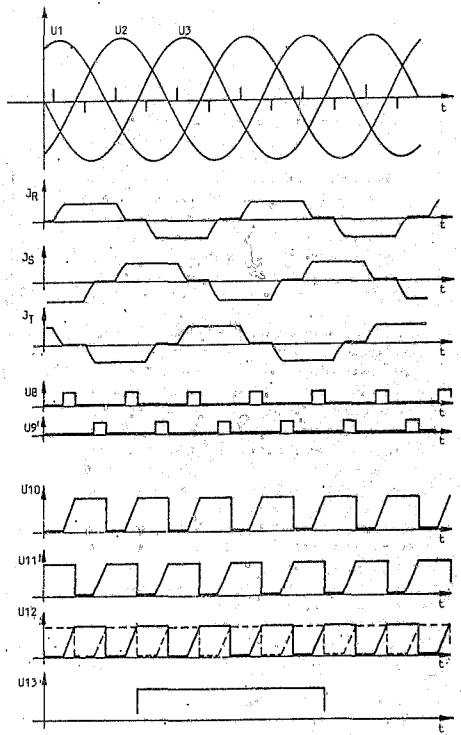


Fig. 4.16 Forming γ actual value by collecting the 6 extinction angles

flip-flops on the arrival of current end and voltage zero crossing pulses at any bridge valve commutation (Fig. 4.17).

Fig. 4.17 shows also the instants t_0 and t_1, at which the current "End" and the "Voltage zero *crossing" pulses are originated by electronic* detectors installed at the measuring section of each valve. The measuring intergrators are fed by the γ pulse signals desplaced by $\pi/3$, as shown in Fig. 4.16.

At each zero crossing of the commutating voltage, when the input signal of one of the two integrators drops to zero and the integration is completed, new information becomes available for the other integrator, which still stores the information from the preceding measurement. The voltage pulses of one commutating group are combined by an OR gate, and are used to clear the intergrator of the other commutating group to allow the storage of the new information (see Fig. 4.13 and 4.16). From Fig. 4.16 it may be deduced that the information is stored by the associated integrator for an interval of $\pi/3$. The combination of the two integrator *outputs through a maximum selector is offered to* the interconnected inputs of 6 sample and hold elements; and each stores the voltage (which is proportional to the respective extinction angle) for one complete cycle.

Only the smallest output signal of the 6 sample and hold elements is chosen by a further minimum selector and such signal is given as the actual γ to one of the γ controller comparator input.

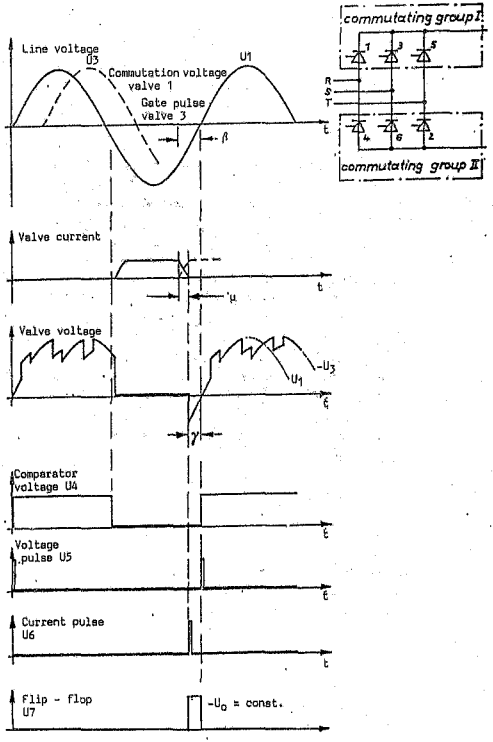


Fig. 4.17 Forming γ actual value for one valve.

The selection of the minimum γ ensures the reliability of the inverter operation and the transient response of the extinction angle control loop.

4.4 Open Control Loops and Firing Control Ranges

The firing angle control must be able to shift the firing advance angle β from a maximum of 85° to a minimum of 30°. The firing advance angle β is limited to 85° instead of 90° to prevent the inverter bridge from falling into the rectifier mode of operation when the angle β has to be largely increased at the inverter DC line side for obtaining a low voltage.

The firing control from 85° to 30° is performed by open control loops which take over the firing control from the closed control loop (γ extinction control) during the transients and for protection purposes during faulty or abnormal working conditions. The open control loops operate by the intervention on the firing control of:

(a) 90° Rate of Change Limiter (Fig. 4.18)

This, in conjunction with the switching on or off processes of the inverter, provides a smooth decreasing or increasing respectively of the firing advance angle β (transient control) in order to avoid voltage oscillations and consequent system instability. (See paragraph 4.6).

(b) Two Pole Current Controllers

Each of these commands the firing of all pole bridges when the DC current drops from its rated value by a quantity bigger than the current margin (see paragraph 3.4). The current margin has been chosen

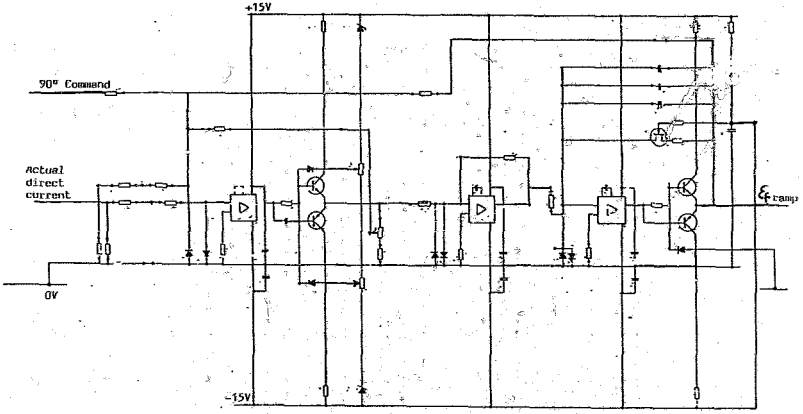


Fig. 4.18 90° Rate of change limiter

around 10% of the established rated current.

(c) A Commutation Failure Detector

This intervenes to shift the advance firing angle to 60° on the occurrence of a valve commutation failure (see paragraph 5.1.7)

(d) Bridge Tripping Logic Circuit

This sends a command to shift the advance firing angle to 150° on the emergency switch off (ESOF)* of the rectifier when the overcurrent diverters operate. (see paragraph 5.6).

The operation of the aforementioned circuits for the shifting of the advance firing angle β causes the open control loops through selective switches (see Fig. 4.19) arranged in the control voltage block. The 90° and 60° firing change-over signals cause the closure of two electronic switches; one for the breaking up of the closed control loop and the other for connecting the voltage related to the required angle to the input of the trigger equipment. The 150° change-over signal causes the closure of the first switch and also both of the switches related to the 90° and 60° change-over signals. Thus the control voltage ε_f which will cause the firing pulses to be shifted up to 150° (rectifier operation of the inverter)* is obtained by adding the two control voltages ε_f for the 90° and 60° valve firing respectively.

Figure 4.20 shows the behaviour of control voltage ε_f, from the instant in which the bridge valves start firing (β = 85°) under the control of the switching-on open control loop or 90° ramp control due to the rate of change limiter, to the instant at which the extinction control

*NOTE: Used in case of power flow reversal.

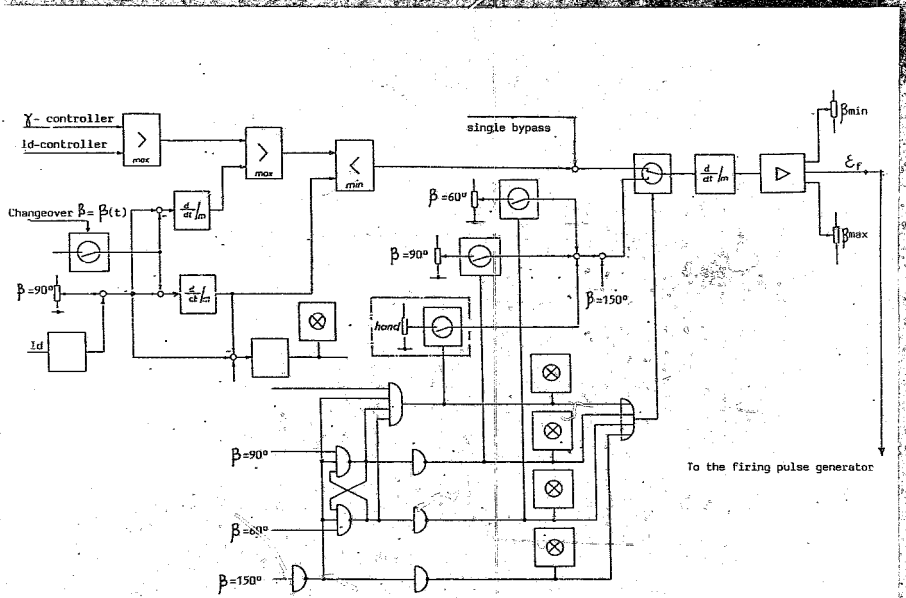


Fig. 4.19 Voltage control and selective switches.

loop takes over (β = 35° reached for Id = IdN);

ε_f varies linearly up to - 3,6 V, at which value the control of firing enters into the dominion of the extinction control. It is very interesting to note that for a while ε_f represents the output of the 90° rate of change limiter (from -5 to -3,6 V) and afterwards the error calculated by the γ controller, which compares at any instant the actual and the reference value (18°) of γ. The behaviour of the inverter DC voltage is also represented in the same figure to emphasise its dependence on the control voltage function ε_f.

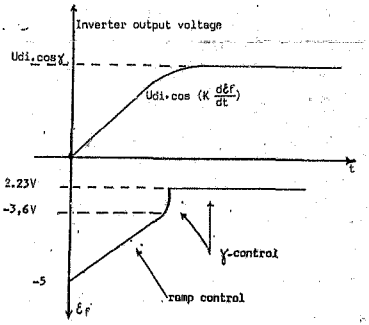


Fig. 4.20 Voltage control and inverter output voltage during transient (bridge switching on).

During the 90° open-loop control, the variation of the firing advance angle follows the variation of $\mathcal{E}_f$ controlled by the control ramp. Consequently γ actual can be expressed from the beginning of the transient switching-on process of the inverter as

$$K \cdot \left(\frac{d\mathcal{E}_f}{dt} + \mathcal{E}_f \right) = \gamma_a$$

where K is a proportional degree factor.

The inverter voltage will thus be represented by the following expression

$$Udi \cdot \cos K \cdot \left(\frac{d\mathcal{E}_f}{dt} + \mathcal{E}_f \right) = Udi \cdot \cos \gamma_a$$

which during the steady condition or under γ extinction angle control since $\mathcal{E}_f = \mathcal{E}_i$ becomes

$$Udi \cdot \cos (K \cdot \mathcal{E}_i) = Udi \cdot \cos \gamma_{min}^{*} = \text{constant}$$

4.5 Firing Control During Transients : SON, NOSOF and FASOF

During the switching on and off of a bridge, the firing of the valve is performed so as to cope with several protective needs for the safety of the valves and for ensuring the stability of the entire plant.

The valves are fired for 10 seconds at the beginning of the switching on process (SON) to ascertain the state of the by-pass firing generator which produces the 100 Hz firing pulses.

This generator is located at a logic circuit (by-pass block) before the final indoor amplifiere provided to give the necessary energy to the firing signals transmitted to

* NOTE: $\gamma_{min} = \gamma_a$

the outdoor firing control blocks. After the aforementioned check and after the bridge has been prepared to be switched on by the removal of all earth links and the closure of the polarity links (related to the direction of the transmitted current), the acknowledgement of the opening of the by-pass link causes the operating of an electronic circuit which, by the intervention of several timers is used to supervise the correct sequence of the final switch-on steps. With the aid of oscillograms of significative quantities and by the representation of the valve firing pulses, Fig. 4.21 shows the time intervals in which several events have to take place, before the bridge can be put in operation.

Instant t_o in Fig. 4.21 marks the start of the electronic by-pass on the generation of the by-pass CMD (function d in Fig. 4.21). This releases the 100 Hz pulse generator to (function a,b) fire only two bridge valves of the selected phase (the first bridge phase available in order to by-pass the flowing current, when the bridge by-pass breaker is commanded to be opened). This by-pass firing situation will continue also after the opening of the by-pass breaker, which normally occurs 220 ms later on the generation of the by-pass CMD. The total duration of the by-pass firing is dependent on the acknowledgement of bridge breaker closure, which has to occur within 120 ms after the opening of the by-pass breaker.

The acknowledgement of the bridge breaker closure determines the change of firing valve from by-pass logic to 90° with ramp firing, which will continue until the γ control loop takes over control of valve firing (see paragraph 4.4). The switching from the one firing control to the other is initiated by the emission of a $\Delta\alpha$ pulse from the by-pass logic circuit immediately after the closure of the bridge

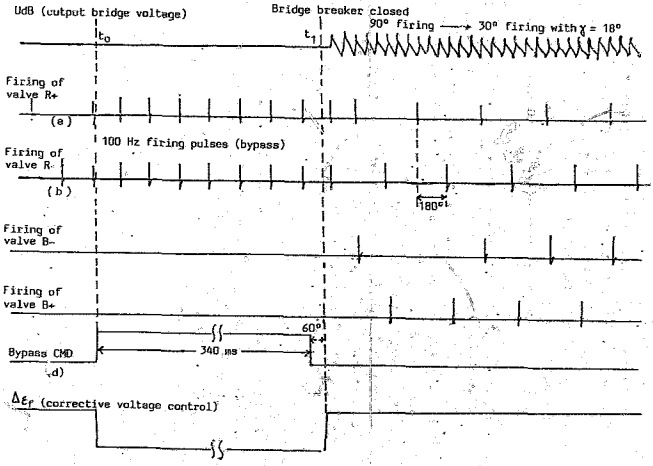


Fig. 4.21 Valve firing during bridge switch-on (SON).

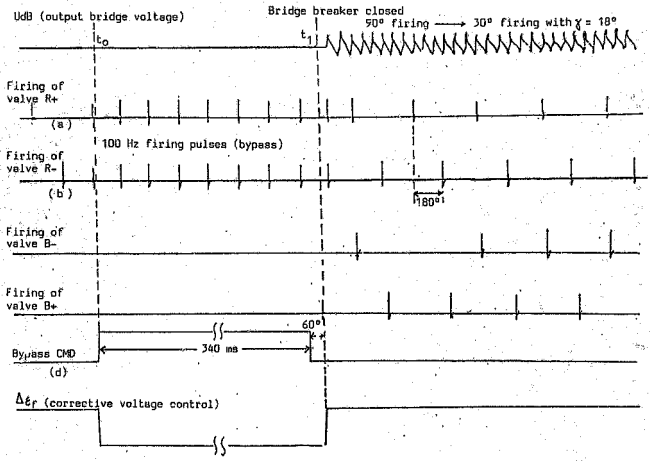


Fig. 4.21 Valve firing during bridge switch-on (SON).

breaker. The $\Delta\varepsilon$ pulse is added to the output of the 90° degree ramp controller to synchronize the new firing (90°) with the voltages across the valves. If the bridge is switched on in absence of current flowing, all the aforementioned steps will take place, but the final firing will be dictated by the inverter current controller (see paragraph 4.4) instead of the γ controller.

Normal switching off (NOSOF) is performed in the reverse way. The first step is characterized by the smooth increase of the firing angle β towards 90° due to the 90° with ramp firing angle circuit, which overrides the control of the γ controller when the bridge receives the command to be normally taken out of operation. The opening of the bridge breaker which disconnects the inverter bridge from the network, determines the by-pass firing (100 Hz) of all bridge valves (3-phase by-pass), to permit a safe reclosing of the by-pass breaker, during the by-pass switch-off interval.

The faster switch-off process (FASOF) on the occurrence of more dangerous faults and failures is characterized by the rapid disconnection of the bridge from the network due to the quicker opening bridge of the bridge breaker (90° degree without ramp). The remaining steps are the same as those described for NOSOF.

4.6 Outdoor Firing Control Circuits

4.6.1 Command Unit and Emergency Firing Pulses

The firing pulses (and any other pulses to and from the valves) are adequately protected from electromagnetic interferences during their journey towards the valves. The protection is ensured by isolating transformer, screened cables and a fibre

optic transmission system in proximity of the valve container.

(The valve container is at the line to earth potential). Moreover each firing pulse (start and stop) is checked and re-built by a processor installed underneath the tank (command units) which may generate protective firing pulses in emergency conditions. The emergency firing pulses are formed on the occurrence of deviations of valve currents and voltages from their normal values as a consequence of AC network and DC system disturbances. The emergency firing pulses are released if at least one of the following conditions arises:

(a) the duration of the negative voltage after commutation of the valve (see Chapter 5) is shorter than the minimum of the 500 μs valve recovery time,

(b) the positive voltage slope exceeds a threshold value after commutation, within the valve recovery time,

(c) the valve current rises above its maximum after falling below the minimum threshold value,

(d) the negative valve voltage does not reach the minimum threshold* after commutation.

In Fig. 4.22 the command unit logic is presented with the main functional aspects of current and voltage detection and the consequent generation of

* Note: minimum and maximum voltage threshold values are used for the determination of the recovery time of the valves.

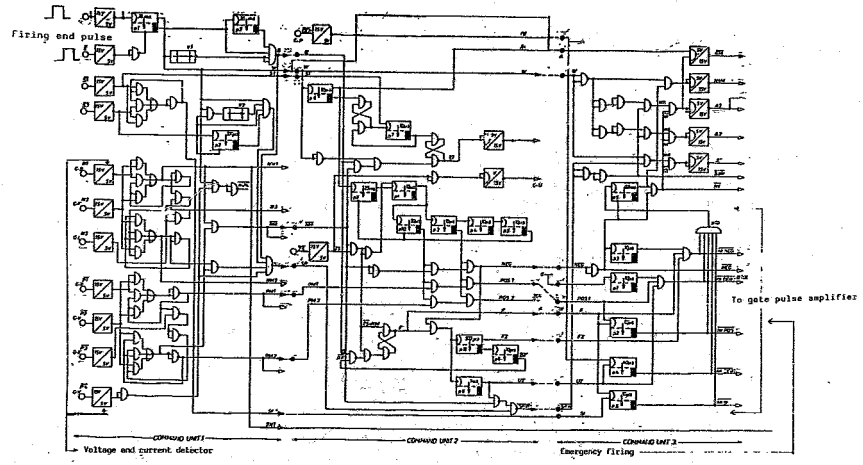


Fig. 4.22 Command unit logic.

the emergency firing (Zamco TSE, 1979c).

4.6.2 Gate Pulse amplifier (by Zamco documentation).

The gate pulse amplifier amplifies trigger signals supplied by the control and monitoring equipment into trigger pulses for the converter valve.

The trigger pulses passed to the valve unit take the form of medium frequency siggle-phase AC and produce turn-on of the thyristors of one valve of the valve unit.

The amplified trigger pulses are transmitted magnetically (see Fig. 4.23).

(a) Signal section

The signal section of the gate pulse amplifier receives its signals from the control and monitoring equipment (command unit) in the form of positive rectangular pulses > 10 V, 50 mA, and negativ peaks of approximately 30 V, both with a repetition frequency of 50 kHz.

The logic of the signal section takes into account malfunctions such as

- insufficient supply voltages
- pulse length not adequate
- time difference between start of (input) trigger signal and (output) trigger pulse > 5µs

- trigger signal present but no trigger pulse
- trigger pulse emmitted although no trigger signal applied
- one of the three parallel input channels exhibits different signal
- insufficient oil flow;

and decides on release of the trigger pulse.

The trigger pulse has the form of AC pulse train with a natural frequency of 5,25 kHz and a repetition frequency of 50 Hz. The amplitude of the 1st half wave of each pulse is 620 A, and that of the subsequent half wave, approximately 300 A.

(b) Power section

The power section operates on the principles of a parallel-resonant circuit inverter. The configuration of the circuit is shown in Fig. 4.23. The resonant circuit consists of the inductance of the triggering cable loop L, the resonant circuit capacitor C_1 and the resistor R (resulting resistances of the gate pulse transformer, gating modules and thyristor gates).

The capacitors C_2 and C_3 act as power storage units for recharging the resonant circuit capacitor or as commutation aid for the load circuit. At the end of the pulse train, capacitor C_4 charges the resonant circuit capacitor to the voltage level necessary for the first

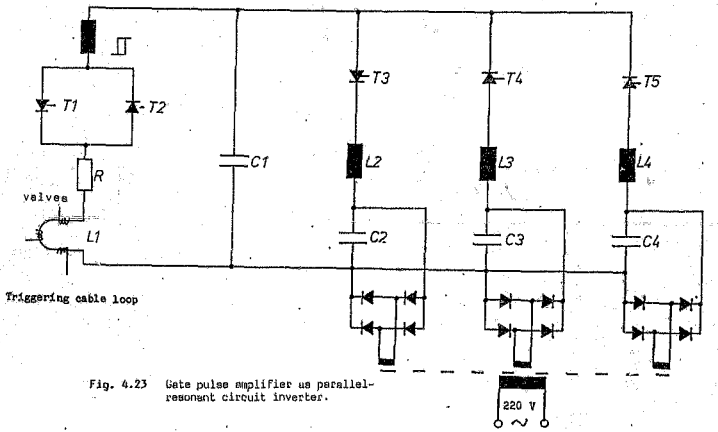


Fig. 4.23 Gate pulse amplifier as parallel-resonant circuit inverter.

trigger pulse. In the steady-state condition this circuit operates as follows (see also Fig. 4.24):

At t_1 thyristor T_1 is triggered and the resonant circuit capacitor C_1 begins to swing over from negative voltage to positive voltage. Before the capacitor voltage reaches zero the commutating thyristor T_3 is turned on at instant t_2 thus accelerating the swing-over operation. At the same time the current in the triggering cable loop is reduced under heavy damping. At instant t_4 the same procedure is repeated with thyristors T_2 and T_4. The resonant circuit capacitor then swings back to the initial voltage. The hold-off interval for thyristor T_1 is given by the spacing of the two current pulses ($t_4 - t_3$). The hold-off interval of the anti-parallel thyristors T_2 is given by $t_1 - t_5$. The positive rate-of-rise of voltage across the thyristors is limited by additional non-linear reactors.

For thyristors T_3 and T_4 the hold-off interval is given by the time between the two load current pulses ($t_4 - t_3$) extended by the time required by the voltage to reach positive values.

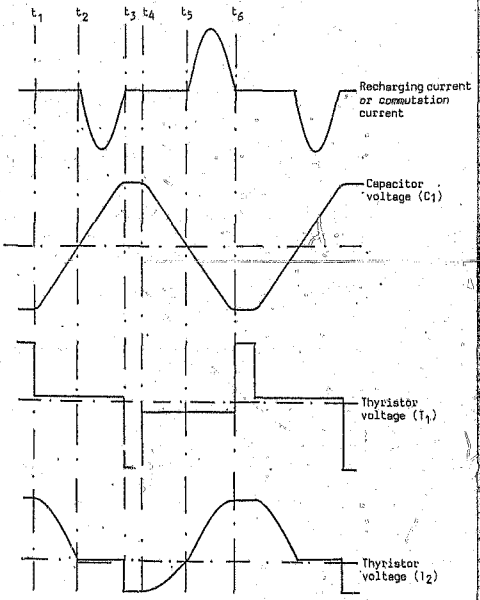


Fig. 4.24 Voltage and current diagrams on the parallel-resonant circuit inverter of the gate pulse amplifier.

SUMMARY

Converter control depends on the AC system voltage and consequently on any AC voltage variation and distortion which might occur, and the related problems were not easily solved. *

A new concept of converter control was developed for the Songo - Apollo system, based on the generation of a variable firing pulse by a digital register (ring counter) which in turn is under the control of a voltage controlled oscillator. The control voltage is formed by

(a) differentiation of a feedback function representative of a conversion parameter (γ extinction angle) with a reference value during the steady-state condition, and

(b) protective devices during periods of difficulties and system voltage instability.

This enables the firing angle control to shift the firing within the permissible angle range.

In addition to the control operations already mentioned, the inverter requirements for constant angle control are achieved by comparing the instant of the delayed end of the commutation signal (current end pulse) with the relevant cross-over pulse (voltage zero crossing pulse). This determines whether or not the valve commutation may take place (described in greater detail in Chapter 5).

The safety angle (γ extinction angle) for valve commutation is preselected and based on a γ minimum linked to the characteristic of the thyristors, with a safety factor added. In this way, ideally the end of the safety angle coincides with the crossover of the valve voltage, or with the end of commutation.

* Further development of converter control systems are in progress.

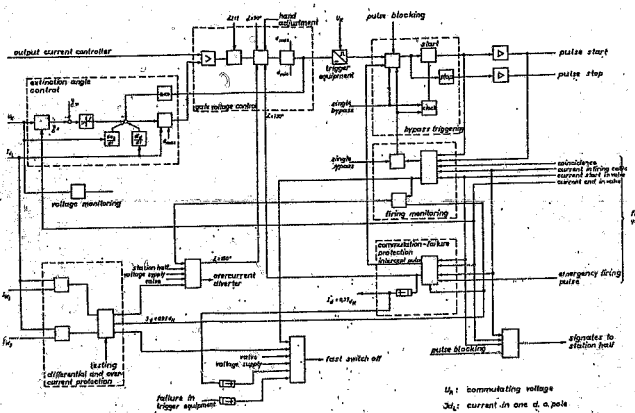


Fig. 4.25 Functional block diagram of the inverter indoor automatic control.

Fig. 4.25 shows the functional block diagram of the control system used at the inverters of Apollo. In the block diagram the monitoring and the protective devices are also represented. They will be discussed in Chapter 5.

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1. Kimbark E.W. (1971) Direct current transmission, 1st ed. *New York: Wiley*, 1971, *vol. 1, pp. 167-174.*

2. Muttelsee, W.; Regowski Y. (1969) Control of the extinction angle of the inverter of a high-voltage DC transmission system, Direct Current Magazine, London, August [illegible], vol. 1, No. 2, pp. 49-53.

3. Fig. 4.6 Zamco, TSE (1979) γ-controller/current controller threshold selector, Cahora Bassa-Apollo document no. 551/TSE-060-str 811, Apollo (Irene, SA), 1979, sheet 72.

4. Zamco TSE, (1979a) Bridge control cubicle, Cahora Bassa-Apollo documentation no. 551/TSE-60-BG811, Apollo (Irene, SA), 1979, pp. 8-19.

5. Fig. 4.11 Zamco, TSE (1979) Time diagram of the pulse generator with ξ_f=0, Cahora Bassa-Apollo documentation no. 551/TSE-60-BG811, Apollo (Irene, SA), 1979, pp. 54.

6. Fig. 4.12 Zamco, TSE (1979) Thyropulse or ring counter, Cahora Bassa-Apollo documentation no. 551/TSE-60-str811. Apollo (Irene, SA), pp. 126.

7. Zamco, TSE (1979b) *Trigger equipment, Cahora Bassa-Apollo* document no. 551/TSE-60-BG811, pp. 42-53.

8. Fig. 4.13 Zamco, TSE (1979) Response of the pulse generator by input control voltage $\xi_f = f(\xi)$, Cahora Bassa-Apollo document no. 551/TSE-60-BG 811, pp. 55.

9. Fig. 4.14 Zamco, TSE (1979) Pulse firing and by-pass logic, Cahora Bassa-Apollo document no. 551/TSE-60-BG 811, Apollo (Irene, SA), pp. 40.

10. Fig. 4.15 Zamco, TSE (1979) Control loop feedback circuit, Cahora Bassa-Apollo document no. 551/TSE-60-BG 811, Apollo (Irene, SA), pp.19.

11. Fig. 4.22 Zamco, TSE (1979) Command unit circuit, Cahora Bassa-Apollo document no. 29.2530 4007, Apollo (Irene, SA), pp. 41.

12. Zamco, TSE (1979) Command unit system, Cahora Bassa-Apollo document no. 29.2530 4007, Apollo (Irene, SA), pp. 1-42.

CHAPTER 5

DC PROTECTION

5.1 Commutation Failure Protection

5.1.1 Definition of Commutation

Valve commutation is the transition from the conducting state to the non-conducting state of the bridge valve and viceversa during the normal working condition of a converter bridge. (Fig. 5.1.1)

5.1.2 Causes of the Commutation Failure

Commutation failure in a valve takes place when the valve is not correctly fired. Abnormal firing is the result of faulty conditions in the firing control system, and leads to the disappearance or delay of the firing pulses, or is the result of AC system voltage weakness or distortion. The AC problems are the more likely cause of commutation failure, and moreover, AC system conditions could involve all bridges of a pole in a simultaneous commutation failure. (see paragraph 5.1.14)

Abnormal firing of inverter valves may also occur during the re-energization of the DC line, if the rate of rise of the energising current is not properly controlled.

5.1.3 Commutation Failure in the Inverters

Since the automatic control system of the inverter has the important task of maintaining the HVDC system

voltage constant, the occurrence of commutation failure in an inverter valve, which causes a sudden drop of the inverter DC voltage, is more serious than the commutation failure in a rectifier valve, because it affects the stability of the HVDC system more adversely. For this reason, commutation failure is constantly monitored at each valve of the inverter bridge and devices have been developed which reduce the influence of such disturbance on the normal behaviour of the HVDC system (Kimbark, 1971a).

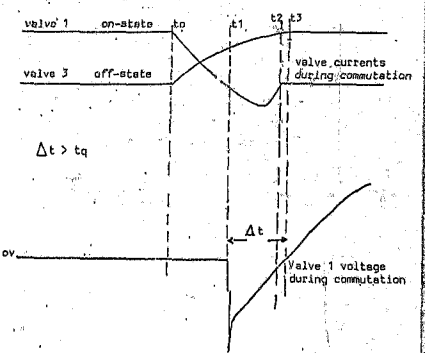
5.1.4 Circuit-commutated Recovery Time and Hold-off Interval (γ_0 Extinction Angle)

Commutation failure in an inverter valve can be the result of an excessive increase of the valve commutation time. This means, as shown in Fig. 5.1.2, that if an off-state voltage (positive voltage) is applied to the valve before the expiry of the circuit-commutated recovery time t_q, the valve will turn on again even without gate current. Commutation failure therefore occurs if the period of the reverse voltage Δ_t (hold-off interval), which corresponds to the γ extinction angle, is shorter than the valve circuit-commutated recovery time t_q.

The circuit-commutated recovery time is a characteristic of the valve thyristors which varies with varying thyristor junction temperature.

The hold-off interval is a characteristic of the circuits used to damp surge negative voltage and to reduce the rate of rise of voltage or current

in the thyristors forming a valve during the turn-off time. The hold-off interval which is equivalent to the γ extinction angle can be set by a suitable capacitor-resistor combination (grading circuits) in parallel with thyristors, and by a series inductance Fig. 5.1.3. The grading or suppression circuit at Apollo inverter station has been set to guarantee a hold-off interval of 1 ms, equivalent to an extinction angle γ = 18° for the thyristor type used which has a recovery time response in the order of 500 µs.(9°) (Heumann, 1975).

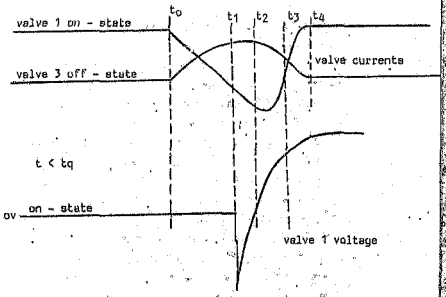


$t_2 - t_1 = t_q$ Circuit-commutated recovery time

$t_2 - t_0 = \mu$ Valve commutation time (overlap time)

$t_3 - t_2 = \Delta t$ Hold-off interval, which corresponds to the γ extinction angle of the valves.

Fig. 5.1.1 Normal valve commutation



$t_2 - t_1 = \Delta t$ Hold-off interval, which corresponds to the extinction angle of the valves

$t_3 - t_1 =$ tq Circuit-commutated recovery time

Fig. 5.1.2 Valve commutation failure. The commutation time is too long and valve 1 returns to the conducting state.

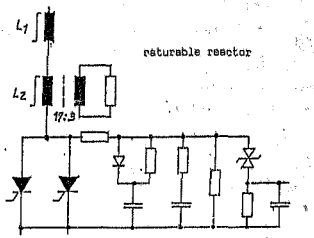


Fig. 5.1.3 Voltage grading network of Apollo valves.

5.1.5 Consequent Commutation Failure in an Inverter

Commutation failure in any bridge valve leads to the collapse of the direct voltage of the inverter bridge for a period which has been calculated to be three eights of a cycle. This decrease of the DC voltage at the inverter side causes a sudden rise in the direct current which in turn prolongs the commutation time. This has the result of creating conditions for the occurrence of new commutation failure, thereby resulting in an additional decrease of the inverter voltage (Kimbark E.W. 1971b). The occurrence of a commutation failure in an inverter bridge is therefore likely to spread to all the other inverters of the affected pole if the rate of current rise after a commutation failure is not properly limited. A solution to the problem of consequent commutation failure has been found with the installation of a DC reactor on the DC line receiving end (inverters). The inductance of this reactor is calculated (by Kimbark), so as to oppose the rate of current rise due to the occurrence of commutation failures.

5.1.6 DC Terminals Short-circuited by the Occurrence of a Bridge Commutation Failure

When a valve fails to commutate, the inverter bridge causes the DC terminals to be short-circuited through the uncommutated valve and the next valve in the valve firing cycle. For example, for a bridge condition in which valve 1 and 2 are conducting, the new bridge configuration should be characterized by the conduction of valves 2 and 3 through the following commutation:

Valve 1 on goes to off
Valve 3 off goes to on

If valve 3 does not commutate, valve 1 fails also to commutate and remains conducting when valve 4 starts to conduct after its ignition.

As shown in the inverter equivalent circuit of Fig. 5.1.4, a commutation from valve 2 to valve 4 after the occurrence of commutation failure on valve 1, causes the DC terminals to be short-circuited by the valves 1 and 4, and that situation of DC terminals short-circuit will continue until valve 4 extinguishes and completes its commutation to valve 6.

Further commutation failures can prolong the duration of the DC terminal short-circuit which increases the instability of the entire system and dangerously stresses the valves of the affected bridges. Therefore several electronic devices have been developed to overcome the problem of a short-circuit of long duration on the DC terminals due to commutation failure.

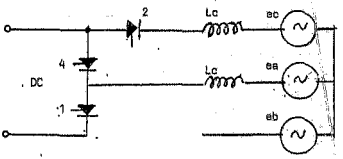


Fig. 5.1.4 DC and AC short-circuit due to bridge valve commutation.

5.1.7 Commutation failure Protection at the Inverter Station

At the inverter station, protection against commutation failures is based on the following concepts:

(a) Reducing the probability of commutation failure due to the disappearance of the firing pulses by automatically switching out the affected bridge before any commutation failures take place. This is done by an additional protective system (valve firing monitoring, see Chapter 5, paragraph 6) which monitors the firing pulses along their journey towards the bridge valves and very quickly switches out the bridge when a missing firing pulse is detected.

(b) Shortening the time during which the bridge DC voltage is reduced to zero as consequence of a commutation failure.

(c) Recovery the DC bridge voltage smoothly from its dump on the occurrence of commutation failure by increasing the valve firing angle from 18° to 60°.

(d) Reduction of the power transmitted by sending a command signal (Idref = 0,3 Idn) originated by the commutation failure detectors at the inverter bridge protection cubicle to the rectifier current controller. That command would cause a power reduction only on the occurrence of a second disturbance within a defined time from the first commutation fail-

ure, or in case of an AC system fault (all bridges of the pole affected by commutation failure).

(a) Outage of the affected bridge if the rate of commutation failures (multiple commutation failures) exceeds a defined value.

5.1.8 The Commutation Failure Detector Input Signals

Fig. 5.1.5 shows the block schematic of the commutation failure detector for each bridge valve at the inverter bridge protection cubicle. The response of the digital electronic circuit detecting the occurrence of the valve commutation failure can be easily understood with the help of the pulse signal diagram (Fig. 5.1.6) at different prominent points of the detector.

Commutation failure detector input signals are defined as the valve status signals.

They are as in the sequence of Fig. 5.1.6.

(a) This current start is generated as soon as the current has reached the value Id=0,25 Idn, after the valve fires.

(b) This current end is generated when the valve current has decreased to a value in the order of the reverse current, and the valve is at its negative reverse voltage.

(c) This emergency firing is generated because of

the danger that the valve may be switched back into conduction when subjected to a positive voltage. (For instance, the γ extinction angle defined by the negative voltage duration is smaller than the settled low limit (0,5 ms). (see paragraph 5.1.4)

(d) This voltage zero crossing is generated at zero crossing of the system voltage when it is rising to the positive from the negative reverse value. Within a certain range across the zero crossing point, the system voltage corresponds to the valve voltage.

NOTE: All the valve status signals are transmitted from the valve outdoor control to the bridge control system through a fibre optic system (light-beam) in the form of 60 V, 10 ms wide pulses. In the bridge control cubicle they are re-sheped to approximately 100 µs wide 10 V pulses before being fed to the commutation detector inputs.

5.1.9 Detector Operation: Intercept and set Pulses

Under normal conditions (absence of commutation failure) the operation of each bridge valve can be represented as a status variable which continuously cycles between the on and off state as the valve is fired. Precisely at each cycle the non-conducting state of the valves is followed by the conducting status (6,6 ms); the transition from one state to the other represents the commutation status or the commutating period of the valves.

The conductivity status of the valves is monitored by flip-flop A (Fig. 5.1.5), which is set and reset by the positive flanks of current start pulses and current end pulses respectively.

The commutation status is monitored by measuring the γ extinction angle as a time period, identified at each cycle by the current end-voltage zero crossing pulse interval (Fig. 5.1.6). Due to the detector AND gate B (Fig. 5.1.5), the commutation failure protection signals can only be generated when the output of flip-flop A and the zero crossing pulse (high level coincidence) coincide, or when γ is more than 50% less than γ_N (18°), since, as previously stated all causes of commutation failure lead to a very small extinction angle. The commutation failure pulse in turn causes the generation of two pulses, called respectively intercept and set pulses, which interrupt the normal valve firing sequence. Furthermore, by causing the inverter bridge to work for a while in rectifier mode, the short-circuit condition on the DC terminals, as a consequence of the commutation failure, is removed. In other words if, for instance, valve 1 (R+) fails to commutate from the conducting state, the consequent intercept pulse will fire valve 5 (B+), meanwhile the set pulse will turn on valve 4 (R-). This means that a simultaneous firing of two different valves is caused by the protection logic (Fig. 5.1.8) after the occurrence of commutation failure in any inverter valve to obtain a negative reverse direct voltage across the inverter bridge (rectifier mode of operation of inverter due to commutation failure protection).

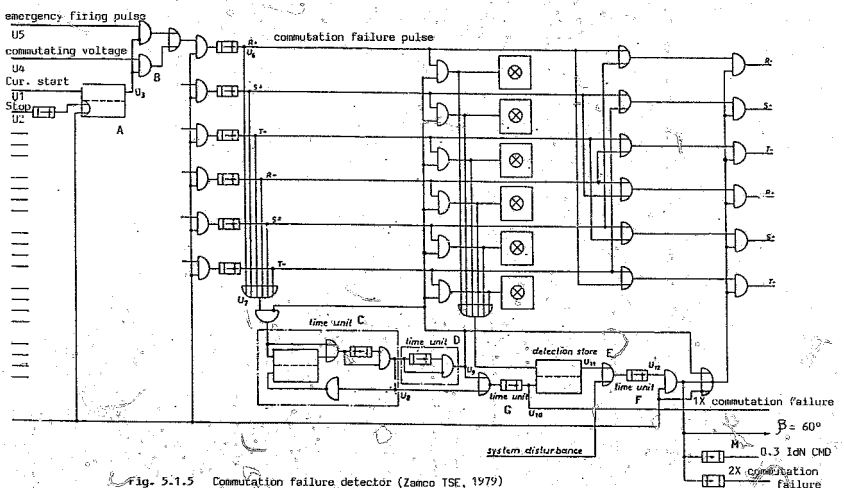


Fig. 5.1.5 Commutation failure detector (Zamco TSE, 1979)

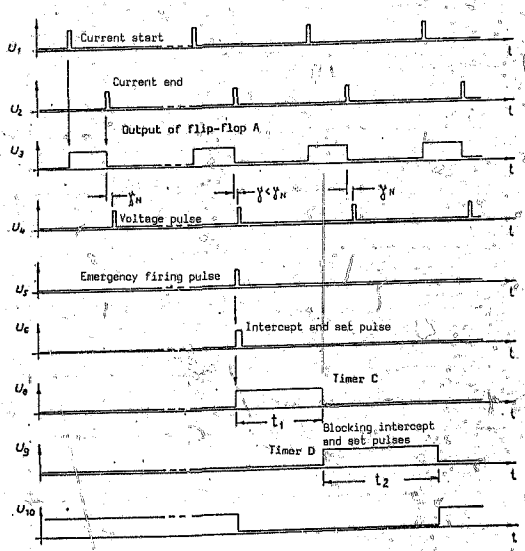


Fig. 9.1.6 Responses by a single dip below the rated extinction angle γ and forming an emergency firing pulse from the valve (Zamco TSE, 1979).

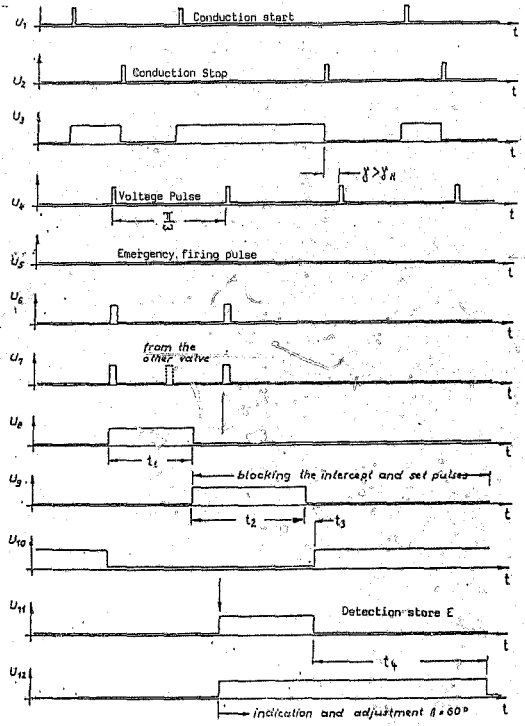


Fig. 5.1.7 Response by commutation failure (without negative valve voltage no emergency firing pulse)

5.1.10 Timer Units of the Commutation Failure Detector

Commutation failure causes the output of a 15 ms timer C to be set (Fig. 5.1.5, 5.1.6) and by such setting, any further commutation failure occuring within this period, causes another pair of intercept and set pulses to be generated (Fig. 5.1.6). On the elapse of timer C, the delay element D is set for 20 ms causing the blocking of intercept and set pulses for each bridge valve, meanwhile the monitoring and displaying channels (6 channels as the valve number) are released. 20 ms is the time during which a commutation fa[illegible]e will initiate the tripping process of the affected bridge through the setting of the detection store E and the time unit F. From what has been previously stated, in the case of a persistent commutation failure, the time units C and D will not change their set condition, and therefore the detection store E and the timing unit F will maintain the outage of the bridge.

It is useful to emphasize that after two consecutive commutation failures within 35 ms for instance, of the same valve, the protective detector enters into the tripping condition and only at the second commutation failure the valve no commutated and still conducting is displayed by the flicking of a monitoring LED.

5.1.11 Advance Firing Angle Setting and Idref = 0,3 CMD to the Rectifier Station

The setting of the time unit F (Fig. 5.1.5) will break the firing valve loop circuit and the output of F will take over on the firing of the bridge

valves with an advanced angle $\beta = 60°$, (see Chapter 4, paragraph 4.4) in order to maintain the bridge voltage conveniently low during the disturbances. Moreover when two commutation failures occur one after the other in such a short time that the timer is not reset on the elapse of 40 ms (see Fig. 5.1.9) from the setting of the time unit F itself (see Fig. 5.1.5), the CMD Idref = 0,3 Idn is transmitted to the rectifier control system so as to reduce the power transmitted of $\frac{1}{3}$. If such reduction does not take place in a time of 120 ms (see Fig. 5.1.9) a command to switch off the bridge immediately (back-up FASCF CMD), is issued by the same logic circuit of Fig. 5.1.5

5.1.12 Real and False Commutation Failure

The commutation failure monitoring channels cannot accurately identify the bridge valve affected by the first commutation failure. In fact the commutation failure of valve 1 (R+), for instance, may be caused by the emergency firing pulse or by the detection of missing current end pulse. Both events may be determined by the failure of the electronics generating and transmitting such pulses and, although valve 1 commutates because of the normal valve 3 turn on, the set and intercept pulses are also generated by the R+ valve detector, causing the inverter bridge to suddenly work in the rectifier mode. We define this type of disturbance as false commutation failure of the bridge. But if valve 3 (W+) fails to commutate from the non-conductivity state, valve (R+) is forced to maintain its turn on state. Again the end current pulse is not generated and the protection operates this

time as intended for real commutation failure. In conclusion, the commutation failure detector has been designed mainly to protect the valve in the conducting condition, but the source of the disturbance is mostly to be found in the switched off valve (Zamco TSE, 1979a).

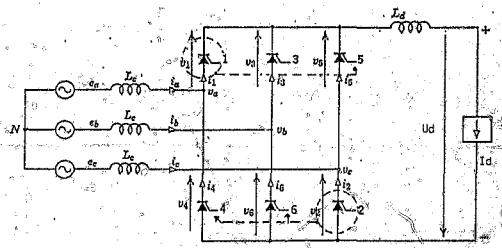


Fig. 5.1.8 Valve 1 and 2 in the conducting condition.

(a) If valve 1 fails to commutate, valve 5 and 6 are simultaneously fired.

(b) If valve 2 fails to commutate valve 5 and 6 are simultaneously fired.

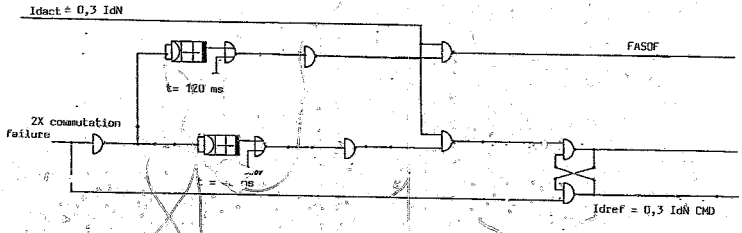


Fig. 5.1.9 Back up Fasof and Idref = 0,3 IdN CMD logic circuit

The oscillograms of Fig 5.1.10 give an example of a false commutation failure due to a spurious emergency firing pulse. The bridge voltage (b) drops suddenly to the negative because of the generation of the set and intercept pulses. The current reference at the inverter side (a) is brought by the setting of the time unit to the 0,3 Idn to indicate the occurrence of a commutation failure and the operating of the relevant detector. No command to decrease the power to the rectifier station has been emitted and the DC system current remains unchanged despite the presence of some oscillations immediately after the occurrence of the commutation failure.

5.1.13 Multiple Commutation Failure and Integration FASOF (fast switch off)

If a certain number of valve commutation failures take place in a bridge during a period determined by the time integrating circuit of Fig. 5.1.11, which through the timer G output (Fig. 5.1.5) is excited at any commutation failure, a bridge switch-off pulse (integration Fasof) is emitted by the threshold circuit at the output of the time integrator itself to prevent the DC system from being affected by severe oscillations. If the rate of the commutation failures is insufficient to generate the tripping signal from the threshold circuit, a long-term repeating commutation failure may take place. In such a case the system voltage oscillations do not reach considerable * proportions because of the damping action of the line reactor. The possibility of operation of the line protection ** which reduces the system current if a pole voltage

* They can jeopardize the inverter operation and stress the valve.
** Voltage dependent current reduction protection (VDCR)

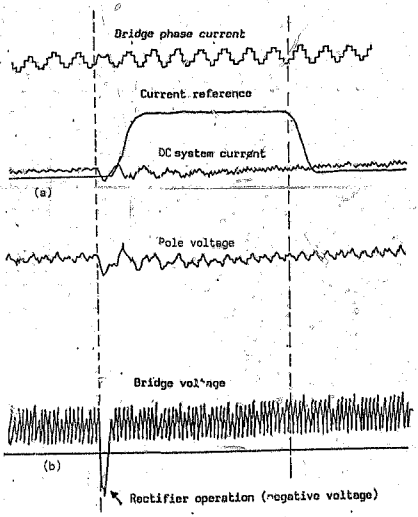


Fig. 5.1.10 False commutation failure due to a spurious emergency firing pulse. (Recorded at Apollo station).

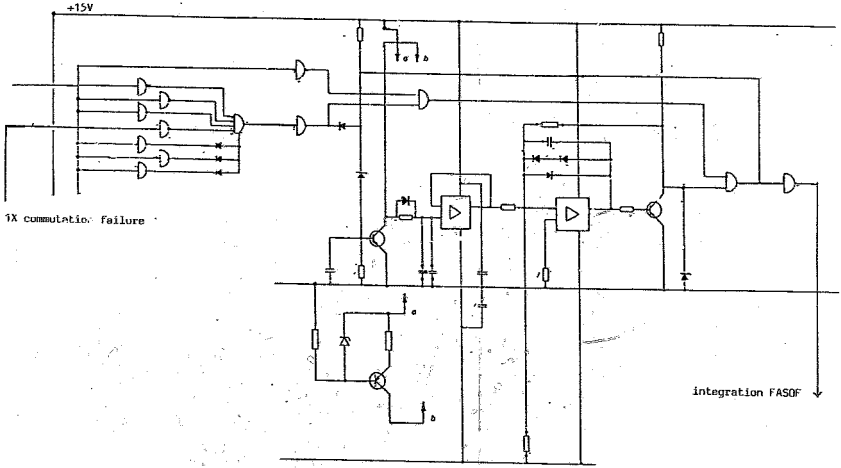


Fig. 5.1.11 Multiple commutation failure time integrating circuit (Zamco TSE, 1979).

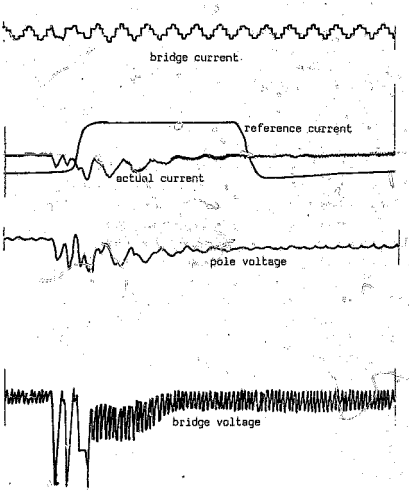


Fig. 5.1.12 Repetitive commutation failures due to a missing ignition pulse. The oscillations on the system arise seriously (recorded at Apollo).

drops below certain specified levels can not be excluded. It is desirable to take a bridge effected by a repeating commutation failure disturbance, out of operation to avoid a sudden decrease in power transmission.

5.1.14 AC System Fault

The oscillograms of Fig.5.1.13 recorded at Apollo inverter station show the behaviour of the various currents and voltages in the inverter, when an AC system fault such as phase to phase or phase to ground flash-over occurs. Focusing on the commutation failure feature it is possible to see that from the instant at which phase W of the AC system starts to reach a relevant alteration or distortion, all the inverter bridges in operation are affected by commutation failure and for the duration of the AC disturbance the commutating conditions for each bridge are no longer defined. For this reason the AC network is continually monitored and in the event of a disturbance which leads to the alteration or distortion of one or more network phases, a signal is emitted by the monitoring circuit to change the status of the time unit F (Fig. 5.1.5) as soon as possible, so that the protective actions described in paragraph 5.1.11 (initiation of bridge tripping and preparation for power transmission reduction) will occur.

5.2 DC Line Protection

5.2.1 Causes of Short-circuits on the DC Lines

The protection of the DC line during line short-

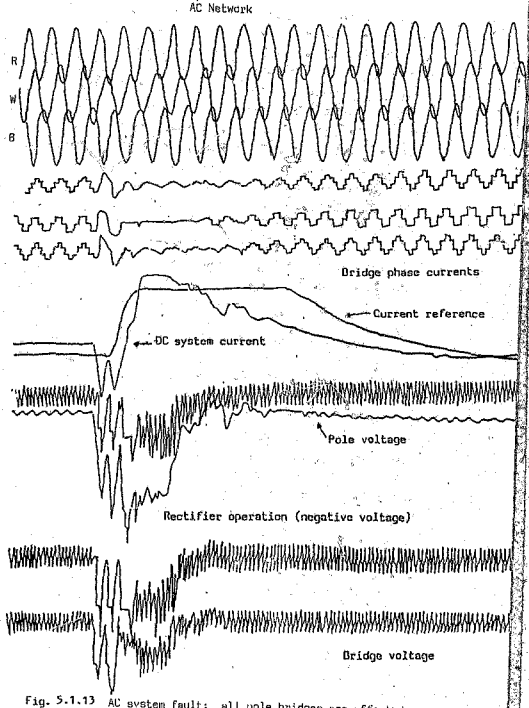


Fig. 5.1.13 AC system fault: all pole bridges are affected by commutation failure (recorded at Apollo station).

circuits is of vital importance in assuring the continuity of power transmission, thought possibly reduced when the rate of flash-over occurrence at the short-circuit point of the line exceeds a pre-established value. Although the DC line is designed to be safe from any flash-over by proper line-span clearances and adequate insulation at the line supporting points, the possibility of short-circuits due to the presence of trees, insulator pollution and bush-fires is very high, expecially in the remote areas through which the lines run and where efficient inspection and maintenance is not always possible. Moreover, weather conditions such as high temperature, humidity and strong wind favour the occurrence of flash-overs when some of the aforementioned causes of short-circuit has taken place (Uhlmann, *1975*).

5.2.2 Basic Principles of Line Protection Design

DC line protection systems are based on the following principles:

(a) obtaining extinction of flash-over as soon as it arises to avoid any damage to the line

(b) holding the line with no power flowing long enough to permit the deionization of the air surrounding the flash-over line points

(c) attempting to restart the power flow in such a way as to avoid undesirable overvoltages on the line

(d) decreasing line voltage drastically after a

certain number of power flow restoration attempts (persistent flash-over)

(c) lock-out of the line (power transmission to zero), if the number of attempts for line re-energization exceeds a predetermined value

(d) lock-out of the line if the flash-over is not extinguish in a predetermined period.

Summerising the aboremention concepts, a line protection system must not only ensure the safety of the line against possible short-circuit occurrences, but must also evaluate the severity of the line faults by a programmed number of line re-energization attempts, and even lock-out the line *if all the attempts are unsuccessful.*

5.2.3 Travelling Waves on the DC Line

The occurrence of a short-circuit at a point of the line gives rise to transient phenomena, manifesting as voltage or current waves propagating in both direction from the point at which the short-circuit occurs.

The propagating waves, also called travelling waves contain an infinite number of components, the fundamental of which depends on the line length, and the speed of propagation.

From the partial differential equation related to the voltage wave propagation

$$\frac{\partial^2 U}{\partial x^2} = LC \frac{\partial^2 U}{\partial t^2}$$

a solution can be obtained which consists of two components:

$$U(x, t) = f_1(x - vt) + f_2(x + vt)$$

The component f_1 travels with velocity v in the direction of decreasing X; while with the same velocity, f_2 is travelling in the direction of increasing X. The wave propagating velocity is a function of the distributed line characteristics and is given approximately by

$$V = 1 / \sqrt{LC} .$$

On a line 1 km from the rectifier end (reference point 0 km), any travelling wave originated at the distance X reaches the reference end (rectifier) and the inverter end in a time $t_1 = x/v$ and in a time $t_2 = (1 - x)/v$ respectively. The travelling waves, due to their high speed (near to the speed of light), can be used to monitor the occurrence of short circuits along the line and to provide the necessary actions in order to prevent dameges to the line.

On the occurrence of a short circuit, the line current and voltage drops suddenly along the line between the fault and the inverter end. The current on the line reaches from the rectifier end and the line point where the fault occurs increases at a very high rate up to the maximum limit allowed by the rectifier current controller. (see paragraph 3.0.2).

5.2.4 The Travelling Wave Protection Signal

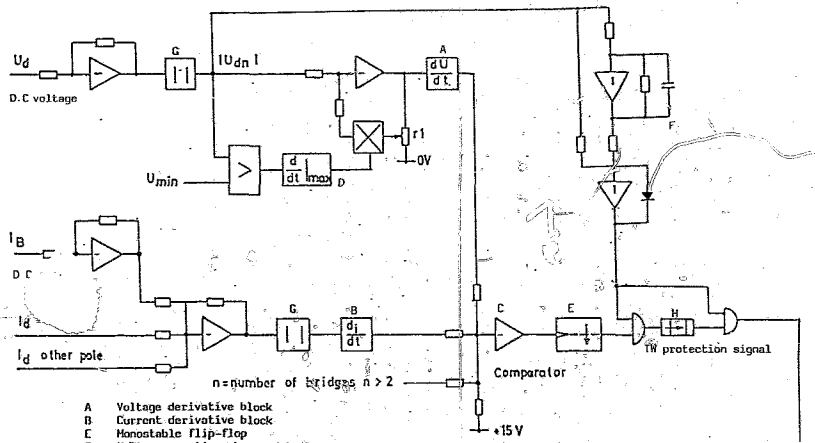
The rate of line voltage decrease and the rate of line current increase at the first instant of flashover are the two travelling wave parameters sensed and measured by the line protection travelling wave detector at the rectifier side. This detector also converts the two measured gradients into appropriate pulses, which are afterwards added together to form the travelling wave protection signal. This signal is memorized by a digital counte. flip-flop, whose change of state causes the shut-down of current transmission by shifting the valve firing from the rectifier to the inverter mode. The block diagram of t e travelling wave detection system in use at Songo is shown in Fig. 5.2.1.

5.2.5 Travelling Wave Detector at the Rectifier

On the occurence of an electrical disturbance on the line, the derivative block A (Fig. 5.2.1) generates the gradient function du/dt related to the change of voltage, and at the same time block B generates the gradient function di/dt related to the change of current.

If the sum of the two gradients reaches a threshold value, which depends on the number of converters in operation, the comparator C changes its output level and triggers the monostable flip-flop D (Fig. 5.2.1 and Fig. 5.2.2).

The threshold value is chosen with the specific aim of monitoring the DC line faults and to make



A Voltage derivative block
B Current derivative block
C Monostable flip-flop
F Voltage negative change detector
G Magnitude generator
D Normalising voltage block

Fig. 5.2.1 Diagram of the Travelling Wave detection system (in use at Songo) (Zamco TSE, 1979).

the travelling wave line protection system operating only on the occurrence of a line fault.

Due to the fact that the line voltage changes over a wide range and as a result the actual rate of the voltage also varies for a fault, the setting of the derivative block A would be extremely difficult. For this reason a corrective circuit block D which normalises any voltage value to a fixed constant, overcomes the obstacle and allows the derivative circuit A to be set at a single rate of change. For rate of current changes the normalizing circuit is not necessary because the power transmission is normally carried out with current close to the rated value.

To ensure correct operation of the travelling wave detection system, the negative changes of the line voltage are also monitored by the operational amplifiers forming the control block F (*Fig. 5.2.1*). The pulse generated by this block and the output of the monostable flip-flop E are combined via an AND element to form a signal which changes the state of the delay-time element H when its width overrides the delay time presented by such element. Only then is the travelling wave protection signal produced by a combination of the voltage negative change detector F output and delay-timer H output via a final AND element. The generation of the travelling wave pulse is shown in Fig. 5.2.2 by the representation of the pulses at the various blocks outputs of the TW detector on the detection of an electrical perturbance transmitted along the line, after the occurrence of a line flash-over.

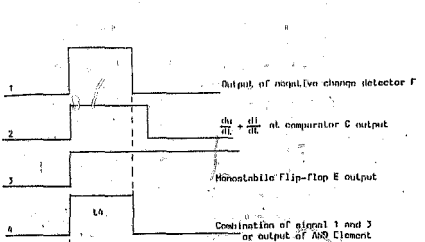


Fig. 5.2.2 When $t_A > t_H$ th[illegible] stection pulse is generated.

5.2.6 Protective Shifting of Firing Angle at the Rectifier End

The travelling wave protection signal is generated a few milliseconds after the occurrence of the line flash-over. This time period varies with the distance of the rectifier station from the point where the fault has occurred. The generation of the travelling wave protection signal has an immediate action on the rectifier current controller, which is forced to shift the firing angle α from the rated value 16° to [illegible]. This means that the bridges working in the rectifier mode are rapidly made to work in the inverter mode, and this favours

the decrease of current within the shortest possible time. In 20 - 30 ms after the occurrence of the line fault, the current reaches zero by the linked operation of the travelling wave protection system and the current controller at the rectifier end.

5.2.7 Travelling Wave Protection at the Inverter End

The inverter station is also provided with a travelling wave detector, mainly to monitor and count the number of flash-overs in a predetermined time period and to lock out the power transmission (Idref = 0 CMD to the rectifier current control) when within such a period, the number of flash-overs exceeds a certain limit.

The protection provided by the inverter travelling wave detector is thus restricted to reinforce the protective action provided by the rectifier travelling wave detector. The protecting intervention by the inverter travelling wave detector is always delayed because of the time-lag necessary for the build-up of the protection signals and their transmission to the rectifier station.

The travelling wave detector at the inverter end is thus not followed by a re-energization system. A memory stage which controls a digital counter for counting the number of reclose attempts carried out at the rectifier end, and a timer which resets the digital counter after a predetermined 5 minute time period, are set by the negative flank of the TW protection flank pulse.

Moreover, a digital stored value representing the number of bridges in operation and the actual value of the line voltage are compared at any re-energization attempt to generate a pulse resetting the memory stages when the attempt is successful.

At the second re-energization attempt the digital counter gives a command to trip a bridge. (Tripping of a bridge at second re-energization attempt is optimal). Such tripping in turn determines a further bridge trip at the rectifier end, so that the subsequent line re-energization attempt will be carried out with reduced line voltage.

5.2.8 The Re-energization of a DC Line after Line Fault Occurrences

The re-energization of the DC line after a line fault is automatically performed by the rectifier current controller, which receives the re-energization commands from the travelling wave detector. The re-energizing commands are issued after a pre-determined time from the occurrence of the line fault to allow adequate deionization of the air surrounding the flash-over path. Normally the time allowed for deionization is made progressively longer for the consecutive faults occuring within a defined period of time (5 min). *
This 5 minute time period has been accepted as the maximum time grouping a series of line protection events caused by the same line fault. By this period of time it is also possible to get an indication of the severity of the fault by counting the number of the events and observing the rate of

* NOTE : The 5 minute line protection timer at Songo and Apollo station is set on the generation of the first travelling wave protection signal.

their occurrence. Nevertheless, the number of reclosure attempts is limited because of the need to avoid stress or severe damage to the line when the fault persists. The last reclosure attempt if not successful, is thus followed by the protection command Idref = 0 which causes the lock-out of the power transmission (Idref = 0 CMD) in a very short time.

5.2.9 Protection and Re-energization at Songo Substation

Fig. 5.2.3 shows the re-energization control system operating at the Songo substation. It consists basically of:

(a) the unit for memorizing the travelling wave protection signals generated by the TW detector (store 1) and by the differential current protection system (store 3),

(b) the unit for the determination of the actual pole voltage,

(c) the shift-register, which selects and controls the setting of the time stages which delay the reclosure attempts for an appropriate deionization.. It also determines the number of the attempts and generates the protection signals when the line faults re-occur persistently.

From Fig. 5.2.4 where the binary signals at the most relevant points of the re-energization circuits are sequentially displayed during the 4 stage re-energization interval, it can be seen

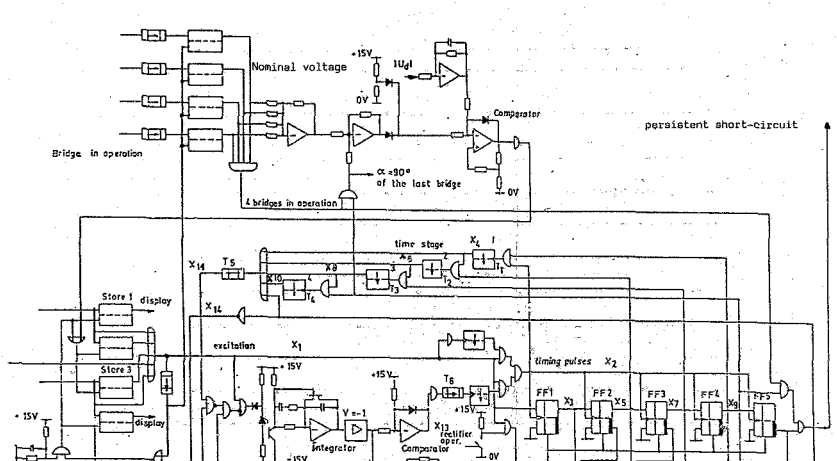


Fig. 5.2.3 Layout of the re-energization system at Songo (Zamco TSE, 1979).

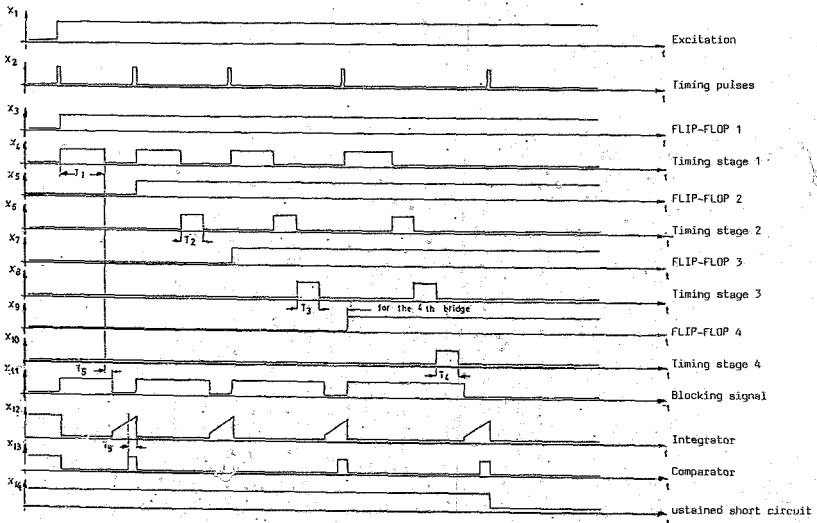


Fig. 5.2.4 Sequence of events during four re-energization attempts (Zamco TSE, 1979).

that the persistence of excitation X1 due to the continuous setting of store 1 or 3 makes the re-energization system work as a 5 pulse ring generator within a period of time calculated from the instant of the fault occurrence and the setting of the last memory element (flip-flop FF5 of the shift-register).

The negative flank of the first timing pulse X2 after the first occurrence of the line fault causes the integrator output X12 to change sharply from high to low by setting the time stage T1. In turn, the integrator output forces the current controller to shift the firing delay angle from α = 16° to 150° and that causes the rectifier bridges to operate in inverter mode so that a fast protective discharge of the line is obtained. After a time T1 + T5 in the [illegible] 240 ms such as calculated for the air [illegible] m before the first reclosure attempt take[illegible], the blocking signal X11 changes from high to low and consequently the integrator output X12 increases firstly as an exponential function (20 ms), and then as a ramp. If the re-energizing ramp continues to rise beyond a certain limit, the comparator output X13 produces a T6 wide pulse, which through the logic input of the shift-register and a delay timer, causes the generation of a new timing pulse X2 (see Fig. 5.2.3).

Therefore a new reclosure attempt will take place on the expiring of a longer deionization time given by the sum of T1 + T2 + T5 (340 ms). The other 2 attempts after the deionization times T1 + T2 +T3 + T5 (440 ms) and T1 + T2 + T3 + T4 + T5 (540 ms) respectively, are allowed to take place, if at each attempt the ramp generated by

the integrator reaches a threshold value so as to get a new pulse at the output of the subsequent comparator stage.

5.2.10 Successful and Unsuccessful Reclosure Attempts

The re-energization command X12 given by the intergrator as an exponential function, followed by the ramp is linearized by the smoothing action of the current controller. As shown in Fig. 5.2.5, at the re-energization attempts the increase of the system current is consequent upon the reference current increased at two different rates of change.

The first rate (990 A in 20 ms) serves to pass very quickly the region of intermittent currents and the second (2 250 A in 126 ms) guarantees a smooth line re-energization and a restrained voltage overshooting.

The criteria adopted to establish whether or not re-energization attempt is successful is based on the measurement of the line voltage during the re-energizing current time. If in that time the line voltage reaches 75% of its final value, the reclosure attempt is considered successful and the comparator of the line voltage detector, shown in Fig. 5.2.3, emitts a resetting pulse to the stores 1 and 3. Consequently the excitation X1 disappears and the restarting circuit is prevented from carrying out a new reclosure attempt.

The oscillograms of line voltage Ud, DC current Id and reference current (Idref) during a line fault

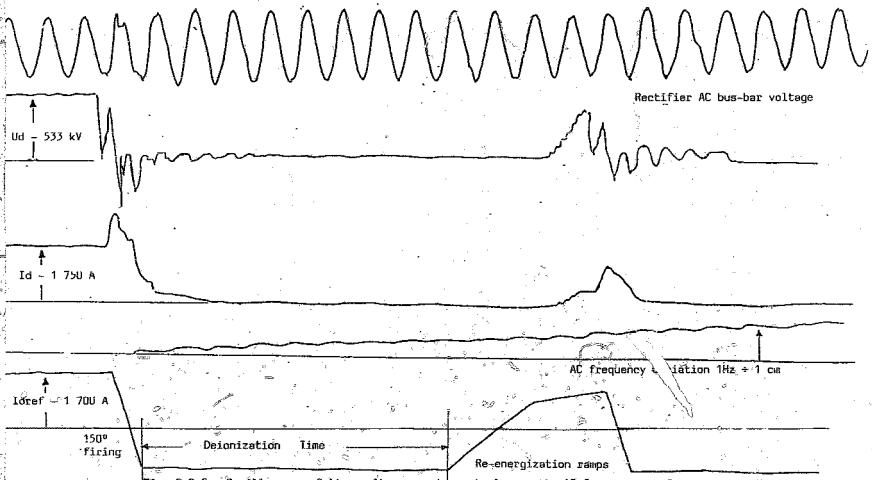


Fig. 5.2.5 Oscillograms of line voltage, system actual current, AC frequency, reference current during flashover occurrence and re-energization attempt (unsuccessful attempt - Songo)

occurrence, are shown in Fig. 5.2.6. In the same fig. the protective action, the line de-ionization time and a successful re-energization attempt are indicated by the behaviour of the pole voltage as well as by the reference current oscillograms (Zamco, TSE. 1979b).

5.3 Differential Protection

The line differential protection system complements the protective action performed by the TW line protection detector.

More precisely, the differential protection system intervenes to protect the line if the TW detector, which responds rapidly to dynamic phenomena, does not carry out its protective function. The differential protection acts only at *steady conditions* by continuously comparing the current injected into the line at the sending end with that at the receiving end.

5.3.1 Differential Protection at the Rectifier and Inverter Stations

At the rectifier end the representative value of current measured at the opposite station and transmitted by means of a PLC system, is compared with the local representative value of the injected current, which is delayed by a slope limiter so as to compensate the time necessary for the transmission of signals from one station to the other. (Fig. 5.3.1).

The slope limiter also provides a smooth current rate of change during its dynamic behaviour after the line fault occurrence.

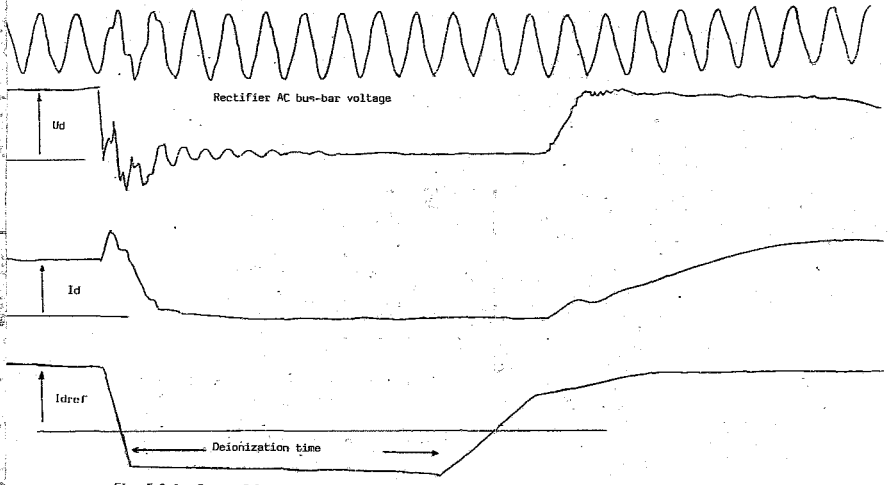
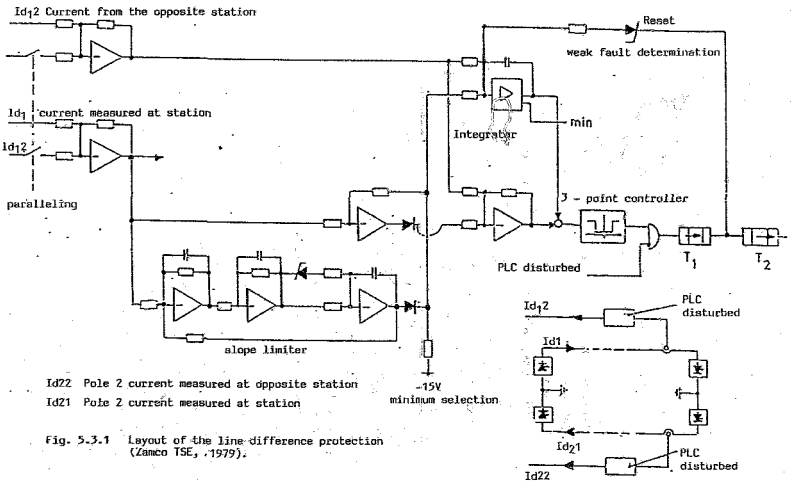


Fig. 5.2.6 Successful re-energization attempt (recorded at Songo).



Id22 Pole 2 current measured at opposite station

Id21 Pole 2 current measured at station

Fig. 5.3.1 Layout of the line difference protection (Zamco TSE, 1979).

The difference between currents measured at two stations is monitored by a 3-point controller (Fig. 5.3.2) which can generate two signals according to the positive or negative sign of the current difference. Because the condition of a negative current difference implies the current at the inverter end is bigger than the current at rectifier end, (which is very improbable), only the positive difference signal is taken in consideration. Moreover the positive difference must satisfy the relationship $Id1 - Id2 \geq Ig$, where Ig is a limit value.

The aforementioned difference signal controls the first of two delay stages in series T1 and T2 through an AND gate. After a total time delay of 220 ms, the output signal of the second stage is memorized by storage 3 at the input of the re-energizing circuit (Fig. 5.2.3), while storage 2 holds the TW protection signal to excite the same circuit. On the occurrence of a line short circuit therefore both storages are loaded at different times (storage 1 before storage 3), and the re-energization attempt, if successful, will reset both of them.

The differential protection system at the inverter station is not substantially different. The slope limiter is replaced by an integrator for smoothing the transients. The delay times of the timing stages are set a little longer (250 ms) and the resetting of the line protection storages will take place at any successful re-energization attempt. The Idref = 0 CMD is issued by the final stage of the digital counter when the last attempt to re-energize the line fails (Zamco TSC, 1979).

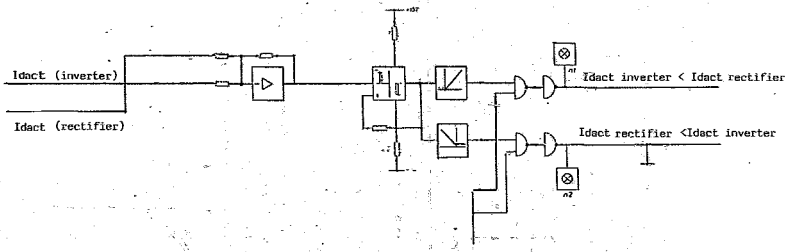


Fig. 5.3.2 3-Point controller to evaluate the difference between currents at the extremities of DC link (Zamco TSE, 1979).

5.4 Line Faults Affecting DC Power Transmission on Bipolar and Monopolar Operation

When a line fault occurs the pole maximum power capability (Chapter 3, paragraph 7.1) is reduced to zero by the protective action of the TW or the differential protection system. An important consequence of this is the rise of the AC bus-bar frequency. The oscillograms of Fig. 5.2.5, show a steady rise of AC frequency, which deviates at around 0,6 Hz from its nominal value after the deionization time and the first unsuccessful re-energyzation attempt. If the DC transmission system is in bipolar mode and the two poles are working at maximum power capability, the module of MPC (Master Power Control, Chapter 3, paragraph 7.1) responsibile for distributing the power between the poles cannot transfer part of the rejected power to the healthy pole. When a line fault occurs, therefore, provisions have been made to trip some generators if the first re-energization attempt fails and the AC frequency increases beyond a certain limit. The frequency at the rectifier station is not expected to rise sufficiently to trip the AC filter if the fault on the line is cleared at the first attempt. If not cleared at the first attempt the AC filters at rectifier end will trip, causing a 10% drop of the line voltage and consequently a reduction of the same order of the power transmitted by the healthy pole. Due to the voltage drop described in paragraph 3.4 of Chapter 3, the inverter control takes over to regulate the current while the current being transmitted is less than the demended current minus the current margin. If the fault persists, the AC frequency continues to rise up to 57 Hz, (Fig. 5.2.5) and is prevented from rising further by the tripping of generators. Before the frequency reaches the maximum limit allowed, a command to trip the bus-coupler is emitted by the MPC to set the AC

frequency associated with the healthy pole back to its nominal value.

After the unhealthy pole has been locked out (power transmission to zero) on the failing of the last attempt, the power transmission on the healthy pole can be restored to its permissible maximum as soon as the remaining generators are re-synchronized and the AC filter operation restored.

If the healthy pole is carrying less than the maximum permissible current, the MPC module responsible for distributing the power causes an immediate increase of the power on the healthy pole up to its maximum transmission capability. This delays the AC frequency from reaching a value where the tripping of some generator cannot be avoided.

It is possible that there is such a surplus of power generation at the beginning of the line fault that the restraint on the increasing of AC frequency by rapidly decreasing the firing angle and a later decrease of the power generation when the AC frequency has deviated 0,3 Hz from its nominal value, is not sufficient to avoid the AC filter tripping and the subsequent decrease of power transmission. Therefore all the foregoing processes in relation to the maximum permissible current transmission might take place (Calverley, 1972).

In monopolar operation, a persistent line fault leads to a total shut-down of power transmission. During the re-energization attempt, the trip of the AC filter and subsequent drop of the line voltage may help restoration of power transmission because the re-energization attempts are carried out at lower line voltage. On the other hand,

some generator must be tripped in order to prevent a black-out of the complete rectifier station. This is because the auxiliary motors can trip due to overfrequency.

5.5 Dynamic Responses at the Generating Plant and Control System for a 50% Load Rejection

Fig. 5.5.1 shows the behaviour of typical generating plant functions in connection with a 50% load rejection due to a persistent DC line fault when power is transmitted in bipolar mode and at the maximum permissible load. At the instant t = 0, due to the load rejection, the generator output decreases very steeply while the AC frequency (curve f.) starts to rise as a result of the kinetic energy increase (turbines speed up depending on the percentage of load reduction associated with each generating unit). A command is emitted at 500 ms by the MPC to increase the DC power transmission up to 1,25 IdN in the healthy pole in order to restrain the frequency rise, which reaches the uppermost limit of 57,7 Hz in 4 sec. A MPC module, on the failing of the first re-energization attempt determines the necessity and the number of generators to be tripped to limit the frequency rise and to assure sufficient generating power to meet the power demand afterwards.

The command to trip some generators (the instant t 4) causes the AC frequency to vary towards its nominal value and just when the frequency crosses it on its way to its undershoot, the generator output moves suddenly to zero and remains at that value for 1 second before it restarts to generate. That kind of discontinuity in power generation can be explained because of the fact that there is no proper coordination between the control of the frequency and the application of the HVDC overload on the healthy pole during 50% load rejection. Moreover, the frequency decreases at

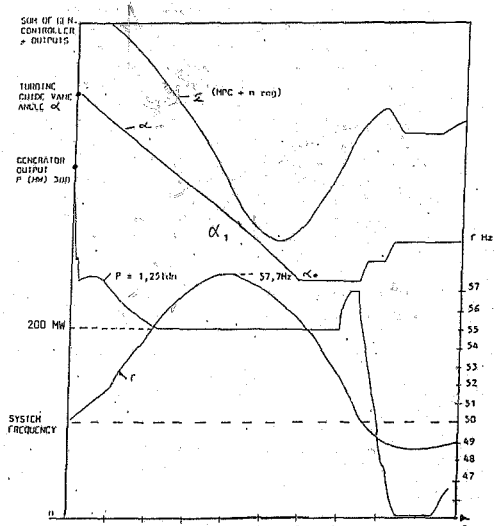


Fig. 5.5.1 Generating plant response for 50% load rejection.

a very high rate after having reached its peak value and that might cause the frequency controller to command load reduction. In other words, the control of the frequency by the MMC is not adequately consistent with the actions taken to decrease the excess of kinetic power when a 50% load rejection takes place. Several control strategies have been suggested in order to eliminate the power discontinuity. "Freezing" the guide vane angle at the peak value of the frequency and overloading the healthy pole so as to create conditions for a smooth decrease of frequency without undershoot when $f > 0$ and $df/dt > 0$ were discussed as a solution to the problem, but finally it was decided to overcome the problem by the installation of dummy resistances to absorb and dissipate the excess power on the occurrence of load rejection. (The dummy resistances and the control system for loading them when necessary has already been designed but not yet put in operation).

Fig. 10 shows the network AC frequency and the imported power at the inverter end when a 50% load rejection occurs.

5.6 Valve Protection

5.6.1 Valve Firing Monitoring

The valves can carry current only for a limited period of time, because after a certain extended period of conduction they would be permanently damaged.

It is of vital importance therefore to monitor them continuously and also to maintain under control all the possible conditions which could cause the valves to conduct longer than their

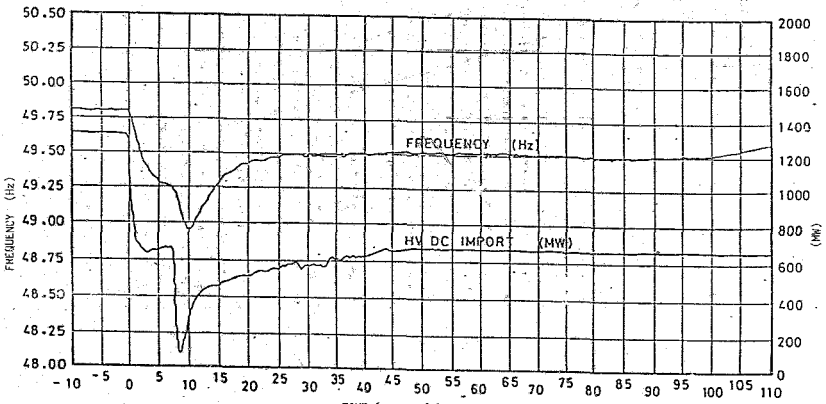


Fig. 5.5.2 AC frequency and imported power at the inverter end.

permissible conducting period of time.

The missing of a firing pulse can cause prolonged conduction of a valve and also commutation failure with the consequences discussed in the related paragraphs. A control system (valve firing monitoring) is provided just to monitor each firing pulse from the point of its generation to the valve gate through the intermediate devices. Should the firing pulse disappear or fail to reach the valve gate, the bridge with the affected valve should be quickly shut-down by the monitoring system.

5.6.2 Differential and Overcurrent Protection

A differential current detecting unit and an overcurrent detecting unit are used to protect the valves from damaging overloads consequent on flash-overs occurring within the bridge area or close by on the DC line. The differential current detecting unit monitors the difference between a burden voltage* representative of the bridge currents flowing in the three-phase transformer feeders and the voltage image of the current flowing in the DC line.

If the difference between the two voltage values exceedes:

a) 20% of the rated DC current for more than 20 ms a fast bridge switching off (FASOF) is initiated

* NOTE: The voltage value representative of the bridge currents is obtained by rectification of each feeder current and by summating the three products of rectification.

b) 80% of the rated DC current and at the same time the voltage representing the bridge currents reaches a value 1.2 times the DC rated current, instantaneous tripping of the overcurrent diverters* is initiated, and the advance angle β is adjusted to 30° (α = 150° at rectifier end) for the inverter whose valves have to be protected from internal short circuits or from short circuits within the station range between transformers and line smoothing reactor.

The difference 20% of the DC rated current represents the threshold value which has been chosen to cause the differential current protection operating in the event the bridge surge arresters fail to reseal and the danger of their explosion may arise (less serious fault).

The difference 80% of the DC rated current interlocked with the bridge current representation bigger than 1.2 times of DC rated current is normally reached for very serious fault (as those abovementioned). In this event the differential protection operates the overcurrent diverters to divert the bridge currents into the circuit formed by the secondary coils of bridge transformer and the transformer feeders short-circuited by the overcurrent diverter closure. Moreover a signal to change-over (see Fig. 4.19) to β= 30° at the inverter (α = 150° at rectifier) is issued in order to prevent any current from circulating in the valves.

The overcurrent detecting units back up the

* See paragraph 5.6.2 - Differential and overcurrent protection.

differential current protection; it operates the overcurrent diverters and adjusts the firing angle when the representative value of the bridge currents reaches a setting value of 3.2 times I_{dN}, which is the maximum current to be expected on the occurrence of a short circuit at the beginning of the DC line.

SUMMARY AND CONCLUSION

Commutation failures at the inverter bridge and line faults are the most frequent faults likely to occur on a DC system transmission and their occurrence may compromise the stability of the system, disrupt the flow of the power and endanger very important equipment of the plant as the valves and the line. For these reasons they, and the protective devices used to prevent further and undesiderable effects on the system, have been discussed in greater detail.

Commutation failure of a bridge is normally a consequence of the distortion or a decrease in the AC system voltage (external fault). If the AC system voltage decreases at a slow rate, the γ controller and tap-changer-controller (see Chapter 4) will be able to avoid commutation failure by increasing β in order to keep γ at rated value. The AC voltage drops at inverter busbar however are in most of the cases the result of faults and disturbances on the AC network, and they take place within microseconds. When very fast changes in the AC voltage occur, it is still possible for the controller to react quickly to the decrease of γ, because the speed of its action is sensibly increased by the rate of increase of direct current and the rate of decrease of AC busbar voltage (see Chapter 4, paragraph 3). In case of severe faults on the AC network the effectivness of the controller in combatting the occurrence of commutation failure is in doubt, and γ cannot be prevented from falling below 9°. Protection systems therefore have been developed (commutation failure detectors), which comes into operation whenever a commutation failure signal has been detected. At the Apollo inverter, the actions performed by the commutation failure detector are:

a) the issue of set and intercept pulses to remove the short-circuit across the bridge

b) the setting of β to 60° in the bridge affected by commutation failure

c) the current transmission on the related pole is reduced to 0,3 I_{dN}

d) the bridge is taken out of operation in case of repetitive commutation failure occurrences or when the duration of the disturbance in the AC system overrides a certain limit.

DC line faults are the most likely faults to occur on a DC system where the converter stations are connected by overhead lines.

The lines connecting Songo to Apollo were frequently affected by this type of fault. During a period of only about a year (1979) when power was transmitted partly at ± 400 kV and partly at ± 533 kV, 300 flash-overs were recorded. This emphasises the importance of the part of the control equipment which protects the line. The action of the line protection circuitry always leads to the interruption of the power flow, which may be resumed after a certain number of re-energization attempts, if the fault is cleared. Clearance of a line fault is obtained firstly by shifting the rectifier firing angle to extinguish the fault current, and secondly by maintaining the "null" power condition for certain times to disperse the ionised air before assuming operation.

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8. Fig. 5.1.5 Zamco, TSE. (1979) Commutation failure detector, Cahora Bassa-Apollo documentation by Podlewski, AEG, no. 551/TSE-60-BG811, Apollo (IRENE, SA), pp. 86.

9. Fig. 5.1.6 Zamco, TSE. (1979) Responses by a single dip below the rated extinction angle , Cahora Bassa-Apollo document by Podlewski, AEG, no. 551/TSE-60-BG811, Apollo (IRENE, SA), pp. 87.

10. Fig. 5.1.11 Zamco, TSE. (1979) Multiple commutation failure time integrating circuit, Cahora Bassa-Apollo document by Podlewski, no. 551/TSE-60-BGB11, Apollo (IRENE, SA), sheet 184.

11. Fig. 5.2.1, 5.2.3, 5.2.4 Zamco, TSE. (1979) Cahora Bassa-Apollo document no 551/TSE-A60-BGB23, Apollo (IRENE, SA), sheet 10/6, 10/27, 10/29.

12. Fig. 5.3.1, 5.3.2 Zamco, TSE (1979) Cahora Bassa-Apollo document no. 551/TSE-A60-BGB23, Apollo (IRENE, SA), sheet 10/13, 11/2.

CHAPTER 6

CONCLUSION

6.1 General

The objective of this work was to collect the fundamental principles and the problems related to a HVDC control system and to organize them in a comprehensive, logical and concise structure, in order to facilitate the understanding of important aspects of DC transmission.

The subject matter has been divided into 3 central chapters covering

a). the general principles and the problems to be overcome by the automatic control, considering the DC transmission system as a whole

b). the performance of the automatic control in connection with the conversion process

c). the most common faults affecting a DC transmission system and the protection devices used.

Therefore the complex control system of a HVDC transmission link has been discussed and presented according to a logical sequence in which the various actions of the control system are motivated.

The purpose of chapter 2 is to provide the background knowledge necessary for a proper understanding of the aims and the role of automatic control in DC power transmission.

The formulas and their derivation have been reduced to the essential minimum, because, although of importance, they are not the purpose of this work. The intent to make the discussion concise has inevitably led to a limited and abbreviated analysis of some aspects of the HVDC control which really deserve a more comprehensive treatment.

6.2 HVDC control and protection

From discussion in the preceding chapters it should be clear that in a HVDC transmission system gate control of the converter valves is used not only for the conversion of power from AC to DC or viceversa, but also for the control of DC power transmission and for clearing faults in the converters (commutation failure and short circuits) and on the transmission line. Moreover the valve gate control is used to delay (rectification) or to anticipate (inversion) the ignition of the valves, but, after conduction has begun, cannot stop it (see paragraph 2.2).

The conduction of the valve can cease only through the action of an external circuit, which causes a reverse voltage across the valve that is to be extinguished.

The circuit external to the conducting valve is formed by the next valve to be turned on and the one which has to conduct for another 1/6 of the firing cycle. In other words, the turning on of the next valve changes the voltage balance on the bridge so as to permit the turning off of the valve to be extinguished.

The ignition of the valve is carried out by trigge-

ring their gates with long duration pulses, allowing a continuous series circuit through two valves in each bridge and thereby ensuring continuous power transmission.

The power transmission is controlled so that the current is held constant while the voltage varies or the voltage is held constant while current varies. These operations are performed by two items of control equipment: the constant-current controller located at the rectifier station and the constant-extinction angle controller at the inverter station.

The constant-current controller measures the direct current, compares it with a set value (reference current) and amplifies the difference between the two values of current to produce a functional error.

This error through a phase-shift circuit controls the ignition angle (delay angle α) of the rectifier valves so as to hold the transmitted current constant.

The constant-extinction-angle controller maintains the line voltage constant. To achieve this, the constant-extinction angle controller regulates the γ extinction angle at a *predetermined value* and rapidly restores it to the desired value when the network voltage changes.

To avoid the current and the power transmission dropping to zero in case of decreases of alternating voltage or due to the loss of some bridge at the rectifier end, the inverter control system is also equipped with a fast current controller, set at lower current than the rectifier controller.

The current controller at the inverter end takes over the current control when the system current drops by about 15% of the rated current; the voltage control in this case is performed by the rectifier current controller.
The characteristic curves of a HVDC system transmission are deduced by the combined actions of the current controllers and the constant-extinction angle controller.
The gate control of the valves is taken over by several protective devices during transients and on the occurrence of faults which may endanger the apparatus and plant or hinder a regular transmission of DC power. Important aspects of DC protection and the related valve gate control have been discussed in chapter 5.

6.3 Future directions

Prior to the Cahora Bassa-Apollo scheme, HVDC schemes did not use digital techniques for the solution of problems related to automatic control. Many requirements for HVDC converter control were met by the use of new digitals techniques at the converter stations at Songo and Apollo. This simplified the converter control circuitry, and has greatly reduced the influence of inherent noise and external disturbances on the firing and monitoring signals. Moreover, the use of this technique provides a fast response of the basic controls, and the performance of fixed logic together with well defined waveforms and firing make testing and fault finding easy. Other parts of the converter control, however, make extensive use of electromagnetic logic which is affected by *air pollution and electro-chemical deterioration.*

Other feature of the converter control at the Songo and Apollo stations is the long distance which the several control, protection and monitoring signals have to travel before reaching their destinations. This compromises the compactness of the converter control circuit, and while the use of different signal transfer techniques (pulse transformers, isolating amplifiers, screened cables and fibre optics) protect the signals from external interference, they also cause distortion and alteration of the signals. Expensive outdoor processors are required to re-shape and re-phase the distorted signals. The long distances also reduce the effectiveness of the monitoring channels, sometimes causing problems with the determination and localisation of particular outdoor faults.

A possible further development of the Songo-Apollo automatic control system would be the replacement of the analogue circuits for the computation of error functions, eg. the difference between set and system direct current (current controllers) and between set and actual values (γ controllers) with digital circuits. The latter provide firing angle correction by first converting the error function into digital form and then by processing it in conjunction with the clock frequency.

The micro-processor and recent developments in micro-processor technology will have a profound influence on control systems of future HVDC schemes, and by their application, many of the aforementioned problems associated with the Songo-Apollo control system will be overcome. Automatic control systems using micro-processors for firing angle correction, and for the generation of protection signals, in conjunction with a purely fibre optic signal transmission technique, have already been designed. A large part of this design work was contributed by the University of Waterloo (Ontario, Canada).

The bold Cahora Bassa-Apollo hydroelectric scheme and the Songo-Apollo DC transmission sytem, despite the adverse affect that the unstable political situation in Mozambique has had on its performance, is a milestone in the not so well known or documented field of DC power transmission. The behaviour of the system is very useful for the formation of operating, control and protection philosophies which could be applied to future schemes.

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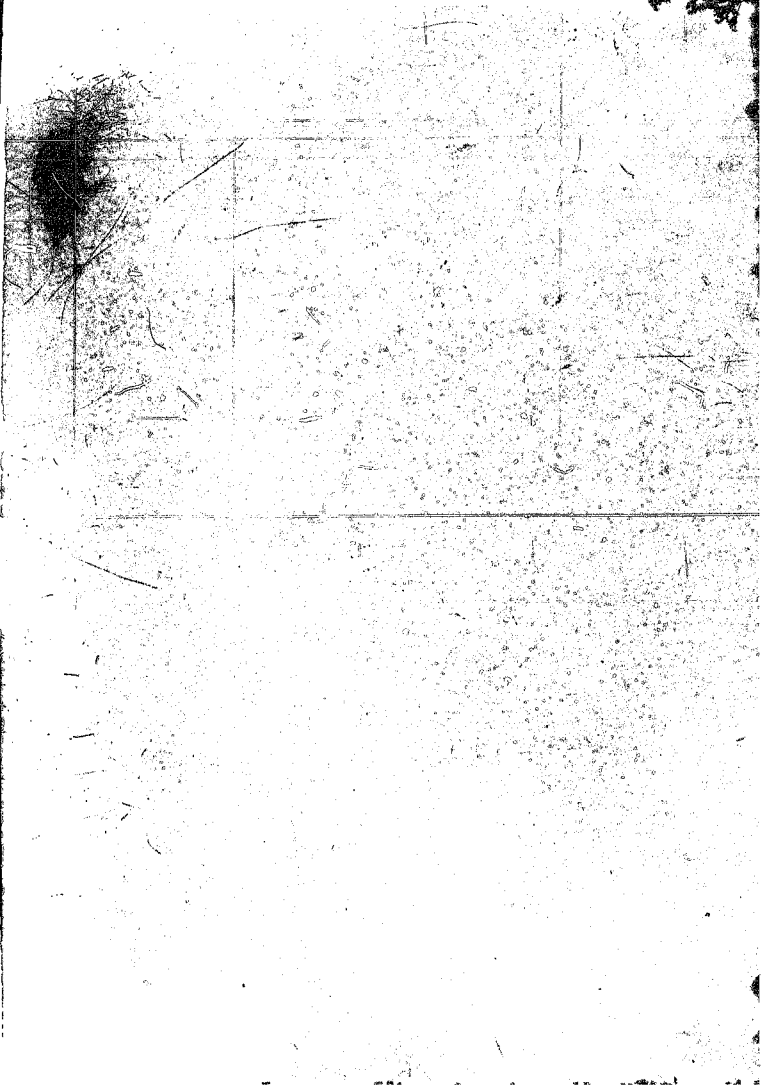
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