A FILTERLESS HVDC GENERATING STATION

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***Abstract* - HVdc generating stations are advantageous for power transmission over long distances. In the case of remote generation, the possibility of operating these systems with generation and rectification equipment intimately connected, with the ac filters removed, has been discussed frequently in the past, with its many advantages presented, but as yet without such a system being realized. Among other concerns, it would seem that the removal of the ac filters is not feasible. In this paper a new configuration is proposed, whereby harmonics are eliminated within the converter, and thus the ac filters may be removed without further implications.**

I. INTRODUCTION

In searching to reduce costs of an HVdc system, considerable effort is invested in devising techniques to reduce costs of the terminals, for these present the predominant costs of the system. In recent years, several papers [1–5] have concentrated in the generating end of an HVdc transmission system, proclaiming that significant capital and operating savings are possible.

The conventional arrangement of a hydro power station which feeds power into an HVdc transmission line is shown in Fig. 1. The basic feature of this scheme is the paralleling done on the high voltage side of the generator transformers. The ac harmonic filters are also connected to this point. A simplification of the previous configuration, as proposed by some authors [4], is shown in Fig.2.

If the generating and rectifying stations are intimately connected, as proposed, there are significant and obvious cost benefits which accrue in the elimination of many components such as generator step-up transformers, high voltage ac switchyard, filters and several ac collector lines between the powerhouse and the ac switchyard. Reliability is also improved because the absence of filters eliminates resonance problems and the risk of generator self-excitation. Moreover, there is potential for variable speed operation to optimize generation efficiency as a function of loading and water head conditions, and potential also for an overall optimization of the machine set (generator plus turbine) with respect to the electrical frequency and mechanical speed [6].

There have been, however, technical concerns raised. Previous studies have shown that the scheme may not operate satisfactorily without the ac filters [7], [8]. The filter elimination allows harmonic currents to flow into the generators with the following important effects on their performance:

1. The generator subtransient reactance forms a part of the commutation reactance, thereby increasing the rectifier commutation angle.
2. Additional rotor-heating and pulsating electric torque due to the flow of harmonic currents.

Although a high pulse number for the rectifier would be beneficial, it never goes beyond 12 due to complicated transformer connections. A recent contribution [9], however, has shown that pulse multiplication is possible. This was achieved by adding a simple circuitry to a basic converter, a 6-pulse bridge, which then became an 18-pulse converter. In this paper the same technique is applied in order to transform the rectifier pulse number from 12 to 36, thus modifying the HVdc generating station as proposed in [1], [6] , but without the technical concerns raised in [7], [8].

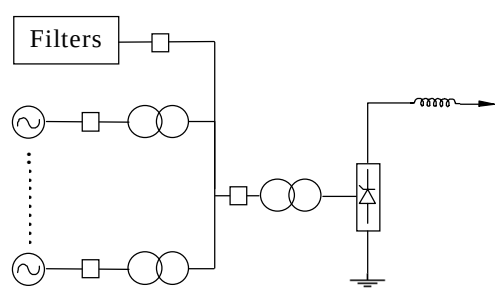

Fig. 1. Conventional HVdc generating station.

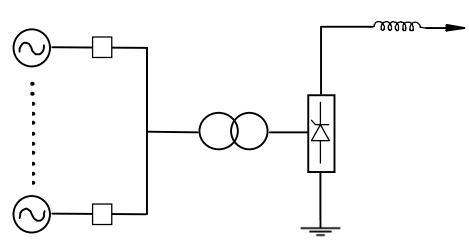

Fig. 2. Integrated HVdc generating station.

II. 36-PULSE INTEGRATED HVDC GENERATING STATION

The traditional HVdc transmission rectifier arrangement is the series connection of two 6-pulse bridges, driven with ac inputs shifted 30º through star/delta transformer connections. Thus, a 12-pulse scheme is obtained at relatively low cost. Fig. 3 shows a modification of the conventional arrangement to permit 36-pulse operation. The additional components, namely capacitors C, transformers T and the reinjection bridge, combine to create voltage v_y, which if added to voltage v_x, increases the pulse number of output voltage v_z. The oscilloscope photograph in Fig. 11 shows experimentally this combination. This is theoretically demonstrated in the following section.

III. OUTPUT VOLTAGE ON THE DC SIDE

A. Derivation of output voltage waveform

In Fig. 3 the capacitors are required to block the dc component of voltages v_1 and v_2 and only ac components are present across the primary side of transformers T. Being v_m a difference, however, it is quite accurate to express v_m in terms of the full values of v_1 and v_2. Thus

$$v_m = \frac{N_1}{N_0} \cdot \left(v_1 - v_2\right) \tag{1}$$

From Fig. 4, during T_1 conduction

$$v_{y1} = v_m \tag{2}$$

Similarly, during T_3 conduction

$$v_{y3} = -v_m \tag{3}$$

Additionally, when thyristor T_2 conducts $v_{y2} = 0$

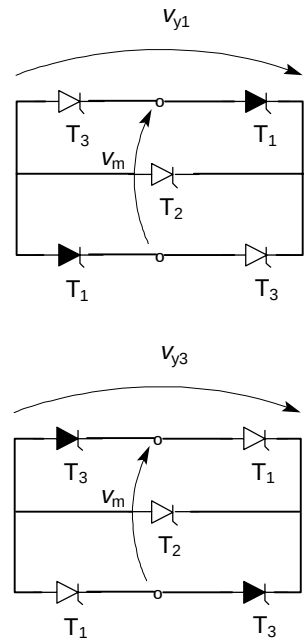

Fig. 4. Voltage v_y when either thyristors T1 or T3 conduct.

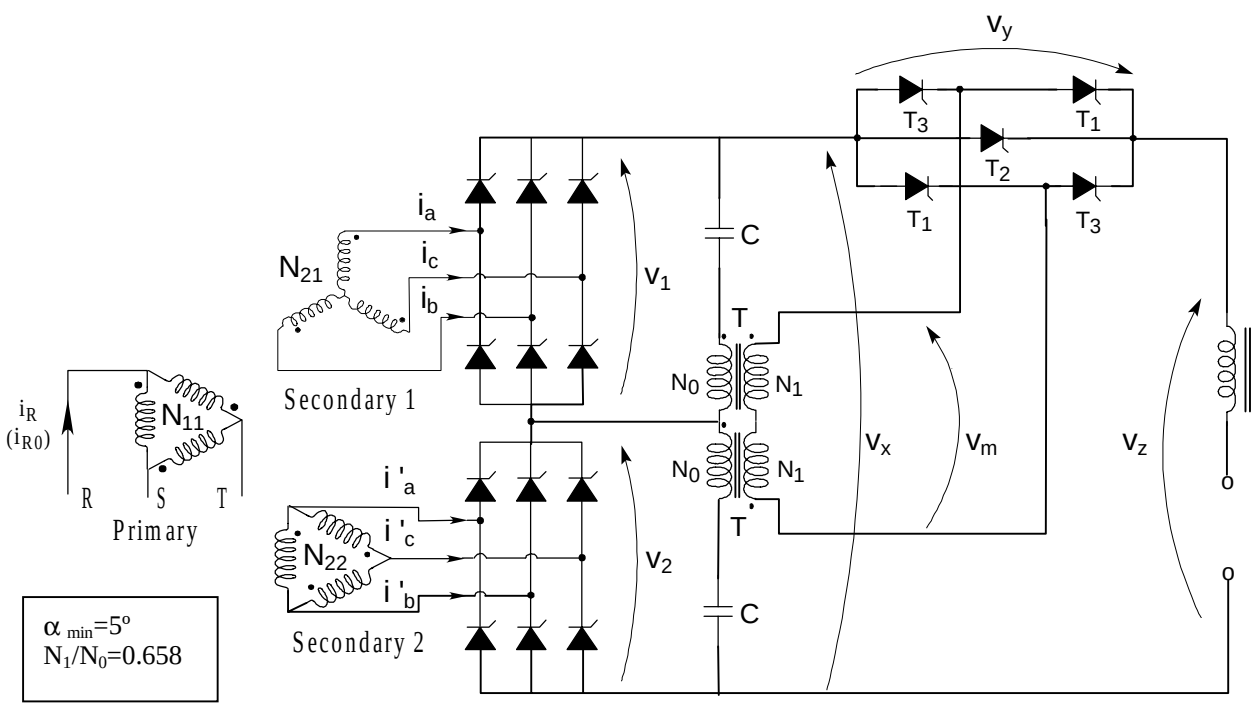

Fig. 3. Proposed 36-pulse configuration.

Fig. 5 shows voltages v_1 and v_2. There are 12 circuit conditions caused by the alternating changes of conducting state of the 12 main thyristors.

Fig. 6(a) and 6(b) shows the phasor diagrams corresponding to circuit conditions 1 and 2. It can be noted that $\dot{\mathbf{V}}_2$ is the same in both diagrams while $\dot{\mathbf{V}}_1$ is 60º phase displaced. The diagrams include also phasors $\dot{\mathbf{V}}_x$, $\dot{\mathbf{V}}_y$ and $\dot{\mathbf{V}}_z$ defined as follows (please refer to (1), (2), (3) and Fig. 3):

$$\dot{\mathbf{V}}_x = \dot{\mathbf{V}}_1 + \dot{\mathbf{V}}_2 \tag{4}$$

$$\dot{\mathbf{V}}_y = \begin{cases} \dot{\mathbf{V}}_{y1} = \dot{\mathbf{V}}_m & ;\ T_1 \text{conducts} \\ \dot{\mathbf{V}}_{y2} = \mathbf{0} & ;\ T_2 \text{conducts} \\ \dot{\mathbf{V}}_{y3} = -\dot{\mathbf{V}}_m & ;\ T_3 \text{conducts} \end{cases} \tag{5}$$

$$\dot{\mathbf{V}}_m = \frac{N_1}{N_0} \cdot \left(\dot{\mathbf{V}}_1 - \dot{\mathbf{V}}_2\right) \tag{6}$$

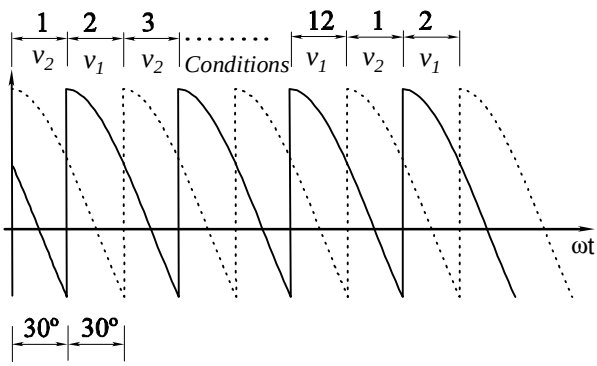

Fig. 5. Voltages v_1 and v_2 and circuit conditions.

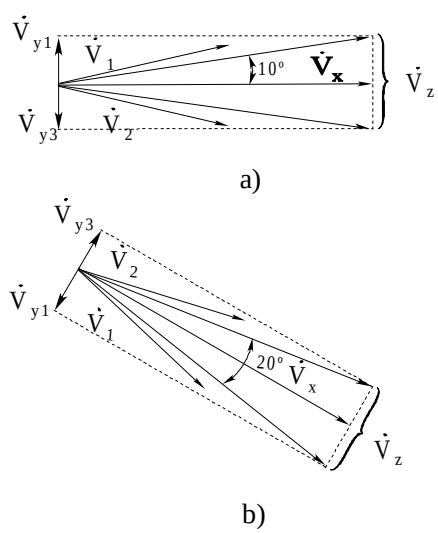

Fig. 6. Phasor diagrams with reference to Fig. 5.
a) Condition 1 b) Condition 2.

$$\dot{\mathbf{V}}_z = \dot{\mathbf{V}}_x + \dot{\mathbf{V}}_y \tag{7}$$

Clearly, if the triggering of T1, T2 and T3 follows the time diagram of Fig. 7, the successive movements by 10º of $\dot{\mathbf{V}}_z$ forms a 36-pulse output voltage waveform.

B. Evaluation of N1/No

From Fig. 6 (a) (by using maximum values)

$$V_m = V_x \cdot \mathrm{tg}(10^o) \tag{8}$$

$$V_x = 2 \cdot V_1 \cdot \cos(15^o) \tag{9}$$

Considering also (4)

$$V_m = \frac{N_1}{N_0} \cdot 2 \cdot V_1 \cdot \sin(15^o) \tag{10}$$

Combining (8) to (10)

$$\frac{N_1}{N_0} = \frac{\mathrm{tg}(10^o)}{\mathrm{tg}(15^o)} = 0.658 \tag{11}$$

IV. INPUT CURRENT ON THE AC SIDE

A. Current analysis on the dc side

With reference to Figure 8 consideration is now given to the behaviour of current ij under the assumption that I_Z is perfectly smooth.

Equating ampere-turns in Figure 8, during T1 conduction

$$ij = \frac{N_1}{N_0} \cdot Iz \tag{12}$$

And during T3 conduction

$$ij = -\frac{N_1}{N_0} \cdot Iz \tag{13}$$

Besides, when thyristor T2 conducts ij = 0. Fig. 9 shows the theoretical waveform of current ij.

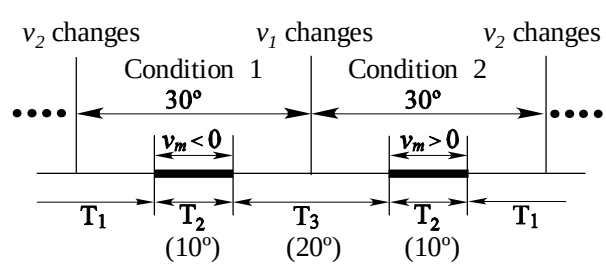

Fig. 7. Firing of thyristors T_1, T_2 and T_3.

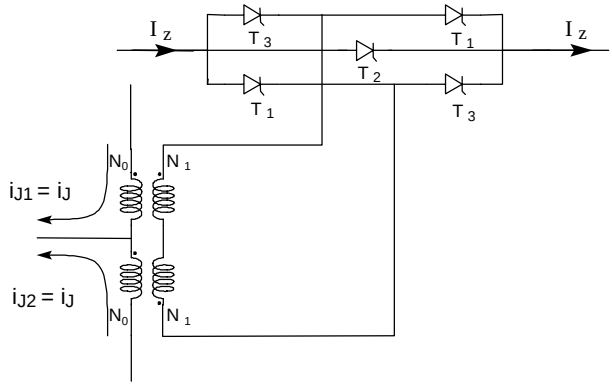

Fig. 8. Currents on the dc side.

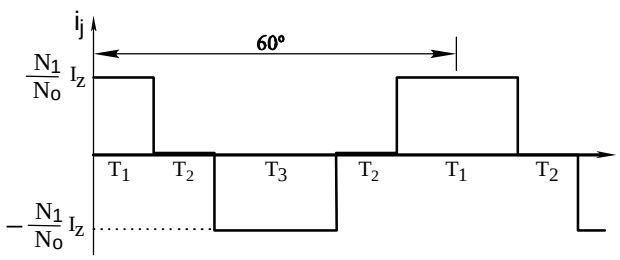

Fig. 9. Theoretical waveform of current i_j.

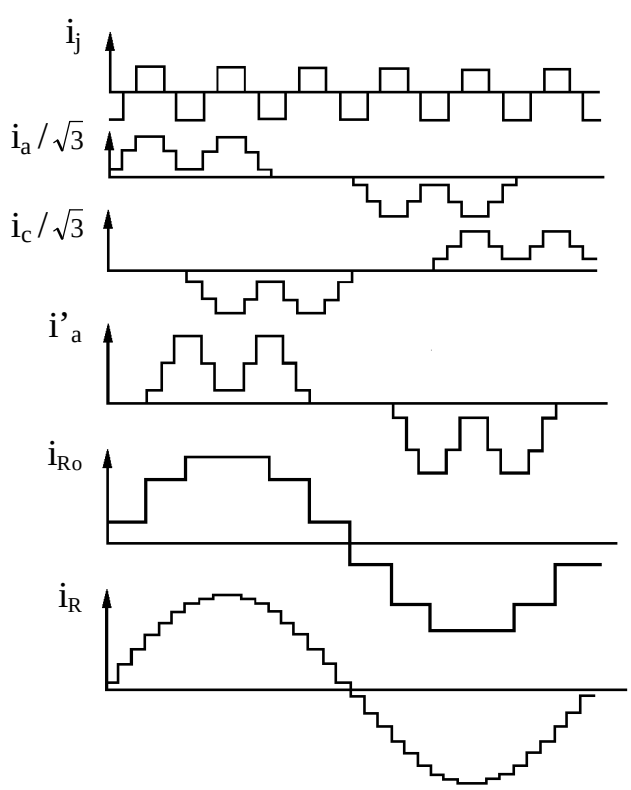

Fig. 10. Theoretical composition of current i_R.

B. Current analysis on ac side

Current i_{j1}, with a frequency 6 times the fundamental, flows in a clockwise and i_{j2} in an anti-clockwise direction, modifying current waveforms in all the windings, including the primary, to finally reduce the ac system current distortion. Figure 10 shows this effect by considering the circuit shown in Fig. 3, under the assumption that $N_{11} = N_{22} = \sqrt{3} N_{21}$.

V. EXPERIMENTAL VERIFICATION

A 2-kW laboratory model has been especially designed to verify the theoretical waveforms described in previous sections and a selection of experimental results are displayed in Figs. 11–14. Diagrams were taken using a signal analyzer HP-3561A and an oscilloscope. A comparison between theoretical and experimental waveforms fully validates the theoretical treatment developed earlier.

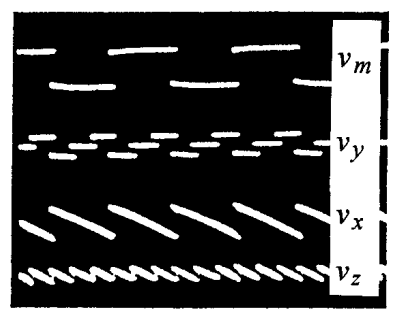

Fig. 11. Oscilloscope voltage waveforms related to circuit shown in Fig. 3.

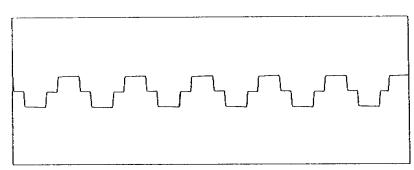

Fig. 12. Experimental waveform of current i_j .

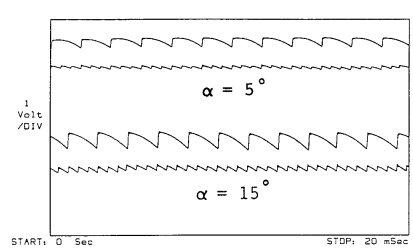

Fig. 13. Experimental dc voltage, conventional and proposed configurations (12 and 36 pulses) .

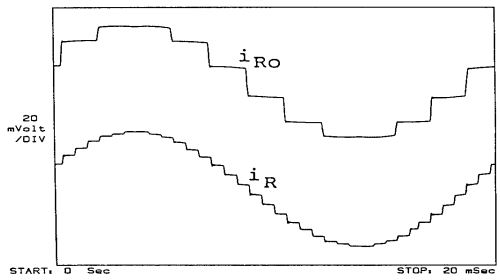

Fig. 14. Experimental ac current, conventional and proposed configurations (12 and 36 pulses) .

VI. ECONOMIC AND TECHNICAL ASPECTS OF THE PROPOSED SCHEME

The economic and technical benefits of connecting the generators directly to the rectifier transformers have been extensively presented in the past [1–6] and can be summarized as follows:

+ Potential for variable speed operation to optimize generation efficiency as a function of loading and water head conditions.
+ Elimination of the ac switchyard and its associated infrastructure, together with filters and one stage of transformation.
+ There is no need for on load tap changers, since the generator excitation system takes over the voltage control.
+ The absence of ac filters eliminates resonance problems and the risk of generator self-excitation. Also severe system frequency excursions (which could be expected in isolated hydroelectric stations) can be better handled.
+ Load rejection overvoltages become more predictable and can be controlled by fast generator de-excitation.
+ High stability of operation and availability to assist in damping power swings on the receiving end.
+ Choice of generating frequency and mechanical speed to give optimum design of generator and turbine.

Technical concerns have also been addressed in the literature regarding the integrated HVdc generating station as follows:

– Generators must absorb harmonics and supply reactive power conventionally provided by filters.
– In the event generators are operated at frequencies other than power frequency, a separate source of power for station auxiliaries must be arranged.
– Special attention is required in the governor and excitation systems to prevent unit oscillations.

One of the most important concerns mentioned above is the one related with harmonics entering the generator [7,8]. The study reported on in this paper, however, indicates that these harmonics can be effectively eliminated within the converter. Also, it is important to note the following:

∗ The size and weight of transformers T in Fig. 3 are reduced by a factor estimated to be inversely proportional to the square root of the operating frequency. Thus, with 300 Hz (36-pulse operation) the respective dimensions can be reduced to 40 % of an equivalent 50 Hz device ($\sqrt{50/300}$ = 0.4). Also, transformers T apply a low voltage to thyristors T_1, T_2 and T_3 for their economic design.
∗ Since capacitors C in Fig. 3 are driven with dc voltages, electrolytic capacitors can be used with considerable size and cost reductions.
∗ Since the only condition for the reinjection bridge is to be in series with the dc current, this circuit can be grounded for an economic insulation design.
∗ The converter can be switched off quickly to 12-pulse operation by blocking thyristors T_1 and T_3 in Fig. 3. This may be useful following large disturbances. A de-blocking action takes the converter back into 36-pulse operation.
∗ Size reduction of the smoothing reactor due to a very low harmonic content on the dc side provided by the proposed technique (please refer to the 36-pulse voltage waveform shown in Fig. 13).

VII. CONCLUSIONS

Integrated HVdc generating stations have been extensively addressed in the past, with its many advantages presented, but as yet without a clear understanding of the effects of the harmonics generated on the performance of the synchronous generator. In this paper the problem has been addressed by proposing a new scheme that eliminates the harmonics within the converter, thereby giving an effective solution to this concern.

Comprehensive laboratory work and computer simulation are presently being carried out to study the behaviour and overall efficiency of the proposed scheme involving full scale systems.

ACKNOWLEDGMENTS

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