# RECOVERY OF ENERGY FROM HARMONIC FILTERS IN HIGH POWER CONVERTERS FOR SIMULTANEOUS PRODUCTION OF OXYGEN AND HYDROGEN FUEL

Farret, F.A.; Parizzi, J.B.; Zancan, M.D. and. Trapp, J.G

Federal University of Santa Maria – UFSM
CEP: 97105-900 – Santa Maria, RS – Brazil
e-mail: faf@ct.ufsm.br; parizzijb@mail.ufsm.br, mdzancan@smail.ufsm.br, jordangt@mail.ufsm.br

*Abstract* – **This paper intends to discuss the energy saving from the harmonic distortion of high power HVDC converters to produce oxygen and hydrogen through water electrolysis. As a result, it is expected a THD reduction and increase of the power and utilization factors of the HVDC converter. This process is based on the use of the energy circulation through the HVDC harmonic filters in an auxiliary converter connected in parallel to the main converter whose control uses the inactive periods of the power converter to result in a better overall power quality. Besides the production of oxygen and hydrogen gases, it is suggested that the filter energy can be also used in other ways as: production of heat, auxiliary services and re-injection of power into the AC system.**

*Keywords* – **HVDC transmission, electrolysis, harmonic minimization, alternative sources of energy, power quality, production of $O_2$ and $H_2$.**

## I. INTRODUCTION

Power quality is a very relevant aspect for cost minimization of generation and conversion systems, as well as for electric power transmission [1,2]. Among the improvement of the quality factors are the reduction of harmonic levels, increase on the power and utilization factors and better efficiency, without burdening the plant costs so much. Parallel to the power quality increase, the modified system has good opportunities in the development of new energy generation and storage alternatives. Use of the energy dissipated in the harmonic filters may contribute in many ways for the quality either of transmission or storing systems. A very convenient form of energy storage may occur in the production of oxygen ($O_2$) and hydrogen ($H_2$) [3,4] for fuel cells and other industrial uses.

The multiple frequency current circulation causes losses in HVDC converters and operation under low power factor turns uneconomical the use of available equipments. To reduce such effects on the transmitted power, many minimization techniques can be used as harmonic filters and increase in the number of converter pulses. Another recent alternative has been proposed [5] with the help of an auxiliary converter in parallel with the main HVDC converter.

This paper intends to show that the energy circulation through auxiliary converters can be used for hydrogen and oxygen production through electrolysis of water. As a result, the auxiliary converter simultaneously minimizes the harmonic content of the HVDC converters otherwise diverted to harmonic filters, increasing so the power and utilization factors. The operation of this second converter uses of the energy present in the "idle time" of the valves of the HVDC converter.

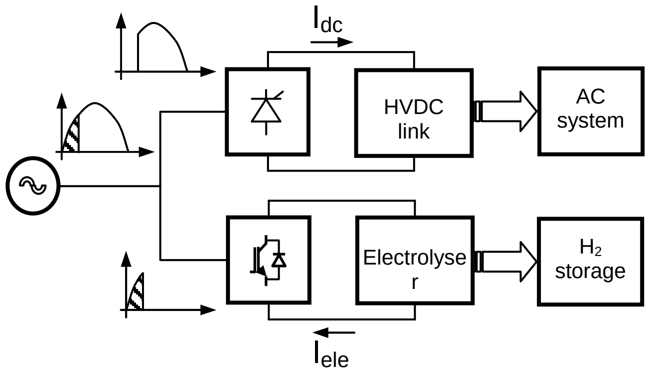


Fig. 1. HVDC converters with idle time recovery of energy.

Due to the distorted voltage present across the converter bus, the output voltage of the auxiliary converter needs to pass by a filtering process before applying it on the $H_2/O_2$ generation plant. Figure 1 illustrates the operation of the set up used in this discussion. The indirect benefits of the hydrogen production, just as described in reference [6], may be, for instance, its use in fuel cells for peak power reduction in distribution and industrial systems. Commercial modules of $O_2$ and $H_2$ production by electrolysis already exist worldwide with pressures up to 25 bar without external compressor and a superior efficiency claimed above 90% [6,7]. With that, the energy recovery system proposed in this paper comes as a good alternative for the market of energy storage. This energy storage form can be indefinitely kept in cylinders always ready for the moment of use, differently of batteries which has lower efficiency in the charge/discharge cycle, higher leakage current, pollutant and high and stabilized costs.

As in any power electronics activity, it is relevant to consider the cost of converters at the early design stages.

Therefore, the addition of auxiliary converters as intended in this paper needs to have a relatively low cost and be of easy implementation. On the other hand, the production plant of $H_2/O_2$ is more onerous. As a compensation form, it is expected a reduction of the harmonic content implicating in smaller harmonic filters and lower cost in such a way than quality improvement of the energy can compensate the investments. On top of this, there will be a reduction in the global cost for improvement of the energy processed as well as the income by commercialization of almost pure oxygen and hydrogen.

## II. ENERGY FROM HVDC FILTERS FOR PRODUCTION OF OXYGEN AND HYDROGEN

For high power (above 1 MW), it seems that the conventional thyristor converter does not have any chose competitor in terms of cost, simplicity, low losses, dominated technology and statistical data [8]. On the other hand, are well known the undesired features and technological solutions for operation of such converters, namely, generation of harmonic currents, inductive and low power factor, among others. Modern power electronics can contribute a lot to minimize technically and economically these problems. As it is well known, the undesired effects of the firing angle on the power and utilization factors, are caused by the current phase control of the firing angle, $\alpha$, to the thyristor gates. To use these effects as a positive advantage, it can be thought that the inductive effect is possible to be compensated by driving the auxiliary converter during these firing intervals when some thyristors chains are inoperative [5].

In this paper, the ripple factor resulting of the use of the waveform portions not used for DC transmission can be easily minimized and perfectly used in industrial processes, even in those sensitive cases to such distortions as it is the case of water electrolysis for production of hydrogen and oxygen. On the side of the water electrolysis, it has to be considered the effects on the ripple factor that, if the electrodes are not special, they will be largely able to accelerate their deterioration.

As discussed in [6], the water electrolysis is an electrolytic process using inert electrodes and aqueous conductive, acid or basic, electrolyte, in which the products of the developed reactions are just hydrogen and oxygen, according to the equation:

$$H_2O \rightarrow H_2 + \tfrac{1}{2}H_2 \tag{1}$$

Such a process is reversible, where energy oscillations indicate that the electric power supplied by the source is equivalent to the variation in the chemical energy in the system, according to the equation:

$$E.Q = -\Delta G \tag{2}$$

where $E$ is the applied voltage, $Q$ is the electrical charge transferred to the reaction and $\Delta G$ is the variation of the Gibbs energy in the reaction.

In terms of the necessary amount of energy from the secondary converter, it can be estimated from the thermodynamic theory to determine losses and the energy conversion levels. Applying the thermodynamic theory to the process of water electrolysis, the minimum voltage for development of the reactions is given for [6]:

$$V_m = \frac{-\Delta G}{n.F} \tag{3}$$

where $V_m$ is the minimum voltage to the electrolysis, $n$ is the number of electrons transferred in the reaction and $F$ is the Faraday constant (96489 Coulombs/equivalent).

In the same way, the thermoneutral voltage, where there is no exchange of heat between the chemical system and the environment, it can be expressed by:

$$V_t = \frac{-\Delta H}{n.F} \tag{4}$$

where $V_t$ is the thermoneutral voltage and $\Delta H$ is the variation in the reaction enthalpy.

The minimum voltage, $V_m$, and the thermoneutral voltage, $V_t$, are directly related to the temperature. Figure 2 presents the theoretical behavior of $V_m$ and $V_t$ in function of the temperature.

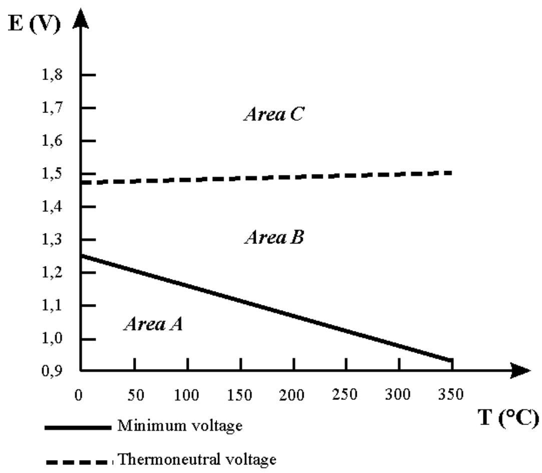


Fig. 2. Voltage versus temperature curves for water electrolysis

The graph of Figure 2 may be divided in three different areas. Area A, below the curve of minimum voltage, represents the area where the water electrolysis does not happen. Area B, between the curves of minimum voltage and thermoneutral voltage, represents the area where happens the water electrolysis, since heat is supplied to the system. Area C, above the curve of thermoneutral voltage, represents the area where happens the water electrolysis, liberating heat to the environment. In practice, all electrolytic cells operate in area C with an applied voltage above the low limit of the thermoneutral voltage. The voltage difference between the necessary voltage for operation of a cell, at certain pressure and temperature, and the thermoneutral voltage under similar operating conditions, is denominated cell overpotential. The operational voltage of an electrolytic cell is given by:

$$V = V_t + n_c + n_a + I.R_0 \tag{5}$$

where $V$ is the operational voltage, $V_t$ is the minimum voltage, $n_c$ is the cathode overpotential and $n_a$ is the anode overpotential.

After obtaining the operating voltage of the electrolytic cell, in order to estimate the parameters of the auxiliary converter, the efficiency is obtained in voltage terms from:

$$\eta\,(\%) = \frac{1.47}{V} \cdot 100 \tag{6}$$

It is important to notice that a voltage above the thermoneutral (overpotential) causes irreversible effect and losses by Joule effect determining the efficiency of the process, conventionally ranging between 75% and 85%. However, well-consolidated and commercial hydrogen production systems based on fuel cell technology may present efficiencies higher than 90% [6,7].

As the operating voltage of a cell must be within reasonable limits, several electrolytic cells are associated in series. In the specific case of electrolysis intended in this work, the high levels of output voltage available to the auxiliary converter will vary according the random variations of the firing angles in the HVDC converter. The moving average current must be a slow process (by modules) to prevent damage to the electrodes. It becomes, then, necessary to make an adaptation in the auxiliary converter by: 1) switching on/off groups (modules) of cells through the control of a moving average increase in the current for the electrolysis process; 2) taking advantage of the low levels of the voltage across the tertiary transformer windings of the HVDC converter.

## III. RESULTS

Improvements in the general indexes of energy quality with the use of an auxiliary converter are: 1) reverse-use of 85% of the harmonic distortion energy processed by auxiliary converters in parallel with HVDC converters for production of $H_2$; 2) the power factor seen by the AC system is higher than 0.95, and sometimes capacitive, for a wide range of firing angles; 3) main converter efficiency is practically unaffected with addition of the auxiliary converter; 4) the utilization factor of the HVDC converter raises from UF = 44.6% when working without the auxiliary converter to UF = 91.5% with the auxiliary converter, considering a maximum firing angle of 60°; 5) THD reductions are up to 50%, especially for high firing angles; 6) reduction of the harmonic filter size (volume and weight) because there is a decrease of up to 60% in their currents; 7) consequent reduction of losses in the HVDC filters by the lower circulation of harmonic currents through.

As reference values, Figures 3 and 4 display, respectively, the waveforms of the output voltage across and current through the auxiliary converter made available by the HVDC converter fitted with a conventional LC filter used to feed the electrolyser, as described in Table 1. Figure 5 displays an enlarged frame of the current through the terminals of the auxiliary converter in a scale especially selected to emphasize the current oscillations. Tis the the oscillatioin made vailable to the electrolyser electrodes.

The HVDC converter simulated in this example operates at a 60MW power and the power in the auxiliary converter is 1.8MW. With this energy is possible to produce approximately 430Nm$^3$ of $H_2$ per hour as described in Table 2. The ripple factor for these voltage and current are, respectively, the electrolyser electrodes whose easily assimilate such relatively low levels of power ripple.

**TABLE 1**
**Data for the HVDC and auxiliary converter**

| | | | |
|---|---|---|---|
| **HVDC converter** | power | voltage | current |
| | 60 MW | 94 kV | 638.3kA |
| **auxiliary converter** | power | voltage | current |
| | 1.8 MW | 11 kV | 163kA |
| **THD (%) with aux. conv.** | without | with | |
| | 15 to 45 | 10 to 14 | |

**TABLE 2**
**Energy available for production of $H_2$**

| $H_2$ **Production** | | |
|---|---|---|
| power | efficiency | $H_2$ |
| 1.8 MW | 85% | 430 Nm$^3$/H |

## IV. CONCLUSIONS

As the major operating time of conventional HVDC converters operate with firing angles of up to 20°, it can be affirmed that, the use of an auxiliary converter connected in parallel with conventional HVDC converters, uses approximately 85% of the energy that otherwise would circulate through the harmonic filters. This energy can be used for production of high degree purity oxygen and hydrogen with high currents and low levels of electrode deterioration. Besides the production of hydrogen and oxygen the innovation here proposed propitiates for the HVDC converter a power factor closer to unit, high operating efficiency, accentuated reduction of the levels of

THD, smaller need of intervention of the harmonic filters and 50% higher utilization factor of the transformer and semiconductors across the bridge arms.

The ripple factor for the voltage across and current through of the auxiliary converter terminals are, respectively, the ones applied to the electrolyser electrodes. These ones can easily assimilate such relatively low levels of power ripple.

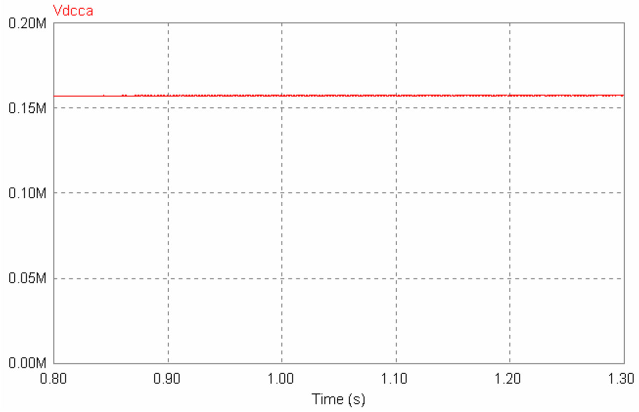


Fig. 3. Output voltage waveform across the auxiliary converter terminals

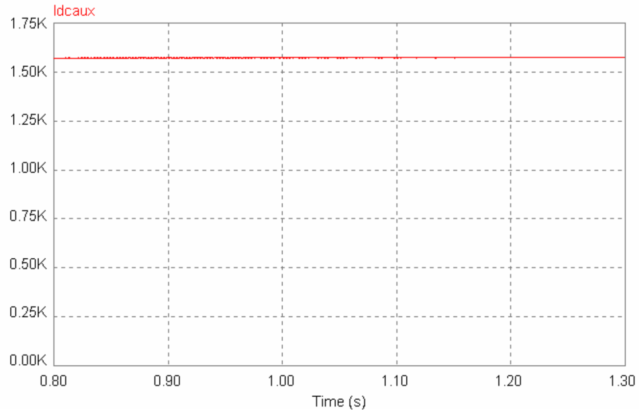


Fig. 4. Output current waveform through the auxiliary converter terminals

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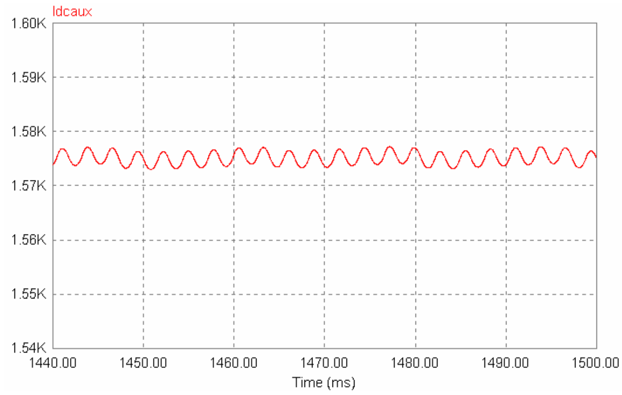


Fig. 5. Enlarged ripple of the current through the auxiliary converter terminals

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