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# A MODIFIED STRUCTURE OF HYBRID ACTIVE DC FILTER IN HVDC SYSTEM

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**Abstract-** Characteristic harmonics that are 12th, 24th, 36th and 48th orders of the main AC frequency of 50 Hz or 60 Hz, may give rise to interference in adjacent telephone lines, distortion of the AC voltages and currents, disturbance in control and monitoring equipments, enhancement of transmission losses and electromagnetic pollution. AC or harmonic component of DC transmission line current, which is superimposed on its DC component, contains mentioned harmonics. Hence, cancellation of harmonic component of DC transmission line current in HVDC transmission system is very important problem. Removing the harmonic component of DC transmission line current is carried out by Hybrid Active DC Filter (HADF). In this paper, a modified configuration of HADF is proposed and has the ability that by proper designing of its passive elements, the nominal voltage-current (nominal power) of HADF active part is adjustable. Theoretical analyses and simulation results prove and validate the accuracy of aforementioned claims.

**Keywords:** HVDC Transmission System, Active DC Filter, Power Conversion Harmonics.

## I. INTRODUCTION

High Voltage Direct Current (HVDC) transmission systems play a very important role in long distance power transmission projects [1]. Recently, HVDC systems have greatly increased. They interconnect large power systems offering numerous technical and economic benefits [2]. The rapid development of power electronics in electrical networks for both industrial and residential customers has led to different network technical problems such as harmonics pollution due to the nonlinearity nature of power electronics devices and voltage problems. The conversions from AC to DC and vice versa are essential tasks in different parts of the network, such as generation, transmission and distribution. This means that harmonics influence both AC and DC sides. The study of mitigation of this sort of harmonics in both sides has become a vital issue [3]. The DC voltage output of the HVDC converter station includes power conversion harmonics with integral multiple frequencies of the main AC frequency of 50-60 Hz. For example, the output voltage of a 12-pulse converter mainly has 12nth harmonics [4]. Since the harmonics will increase transmission loss, disturb control and monitoring equipment and cause electromagnetic pollution, the power filters generally are installed to suppress harmonics and improve power quality (PQ) [4].

The active power filter (APF) which is based on power electronic technology, has better self-tuning ability and better filtering performance than the classical passive power filter [4]. Presently, a shunt hybrid active DC filter (ADF) is widely adopted in the DC side of the HVDC converter to suppress harmonics [4]. This filter consists of a single-phase APF and a single or double tuned passive filter (PF), which is connected in series with each other [4]. Different control methods of the hybrid active DC filter have been proposed, such as the direct converter output voltage control method, the transmission current feedback control method based on system compensation [5-6], the method combining the direct control and the transmission current feedback control [7], etc. Since these methods are based on system transfer functions, the harmonic suppression effects depend on the accuracy of the circuit model. In addition, errors and delays in the measurement, control, and converter driver will further deteriorate the harmonic suppression effects [4].

In [8], a low-gain self-induced feedback control method has been presented to control the HADF for elimination of harmonic component of DC transmission line current. This method has a considerable harmonic elimination power, a very simple structure which has approximately covered all the disadvantages of previously presented control techniques.

In this paper, the control method mentioned in [8], has been applied to control the HADF. In addition, based on the conventional HADF configuration used in [8], a modified configuration for HADF is proposed in this paper. The proposed configuration has the ability that by proper designing of its passive elements, the nominal voltage-current (nominal power) of HADF active part is adjustable. Reduction of nominal power of HADF active part, very low DC supply voltage for HADF, elimination of coupling transformer, reduction of complexity of

HADF structure in comparison to its prior form presented in [8], are the major advantages of the modified configuration. Theoretical analysis and simulation results prove and validate accuracy of aforementioned claims.

## II. CONFIGURATION OF HADF

Figure 1 is the diagram of the conventional HADF on the HVDC converter side which has been used in [8] and Figure 2, indicates the equivalent circuit of the Figure 1.

In this paper, with several small changes and modifications in the structure of conventional HADF shown in Figure 1, a simple model for HADF has been obtained and indicated in Figure 3.

In fact, the modified configuration is obtained by elimination of coupling transformer from conventional HADF configuration used in [8] and dividing the inductance of passive filter $L$ to the inductances $L_F$ and $L_P$.

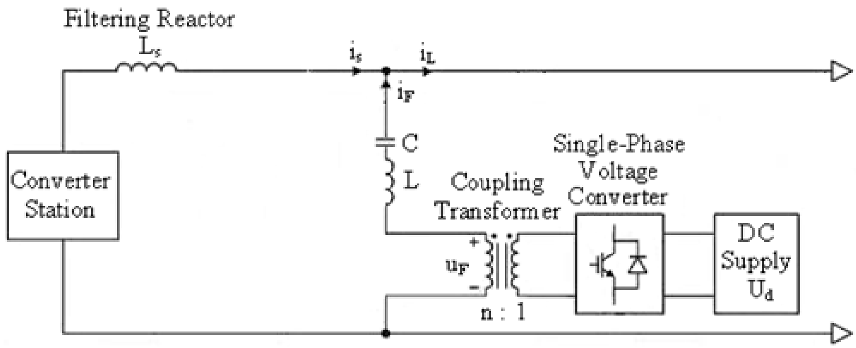


Figure 1. Diagram of HADF used in [8]

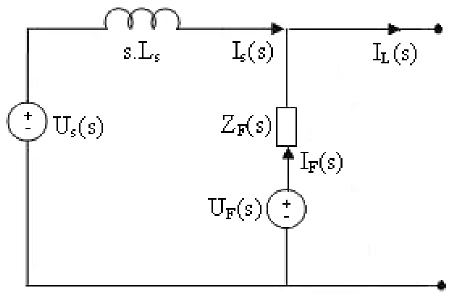


Figure 2. Equivalent circuit of Figure 1

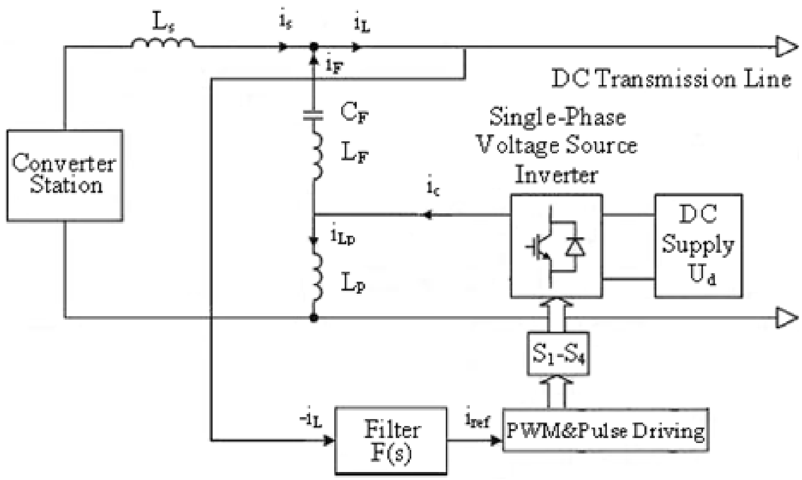


Figure 3. Diagram of the modified HADF configuration

According to Figures 1 and 2, the active part of the HADF is modeled as an equivalent voltage source. So in the modified configuration, the active part of the HADF is modeled as an equivalent current source.

In the modified configuration, active part of the HADF operates as the controlled current source. In fact, this type of filter injects the harmonic compensating current to DC transmission line to suppress the harmonic current (AC component) generated by HVDC converter. Active part of HADF injects a current controlled harmonic current to DC transmission line. So inductance of the single-tuned passive filter must be divided to two inductances $L_F$ and $L_P$.

A single-phase full-bridge inverter controlled by DC transmission line current operates as the active part of proposed HADF. Active part of the HADF can be expressed as the active DC filter (ADF). Modified HADF configuration generates the compensating harmonic current with a significant reduction in its nominal power in comparison to other types of HADF. Reduction of nominal power (nominal Volt-Ampere) in active part of proposed HADF configuration is obtained as for the following features:

1. Voltage drop of main frequency often is in the across of passive filter capacitor $C_F$. So, the ADF requires a very low DC supply voltage.
2. With optimum selection of values of inductances $L_F$ and $L_P$, an optimal nominal value of voltage-current is obtained for single-phase full-bridge inverter. So the coupling transformer is not requiring in the ADF structure. Figure 4 shows the equivalent circuit model of HVDC converter with modified HADF configuration shown in Figure 3.

Where in the figure, $U_s(s)$ is the harmonic voltage output of HVDC converter, $L_s$ is the inductance of smoothing reactor, $I_s(s)$ is the harmonic current generated by HVDC converter, $Z_F(s)$ is the impedance of single-tuned passive filter, $I_F(s)$ is the harmonic compensating current of passive filter branch, $I_c(s)$ is the harmonic compensating current generated by active part of the HADF, $I_L(s)$ is the DC transmission line harmonic current and $Z_L(s)$ is the impedance of DC transmission line and remote load.

The active part of HADF, injects the current $I_c(s)$ to the DC transmission line as follows

$$I_F(s) = -I_s(s) \quad (1)$$

If the modulation index is less than 1, the HADF operates as a current source controlled by current $i_L$. So $I_c(s)$ can be written as follows:

$$I_c(s) = -N(s).I_L(s) \quad (2)$$

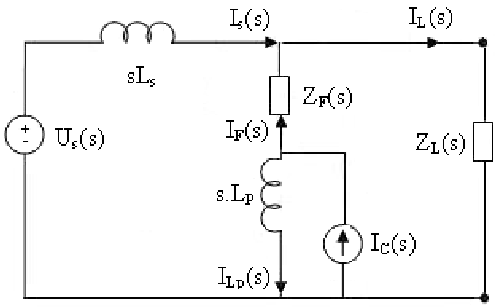


Figure 4. Equivalent circuit of HVDC converter with the modified HADF configuration

where $N(s)$ is the control coefficient, so circuit model of the converter station can be described by Figure 5. According to modified HADF configuration shown in Figure 4, $N(s)$ can be expressed as follows:

$$N(s) = 1000.F(s) \quad (3)$$

According to Equations (2) and (3) and Figure 3, the current $I_c(s)$ can be expressed as follows:

$$I_c(s) = -1000.I_{ref}(s) = -1000.F(s).I_L(s) \quad (4)$$

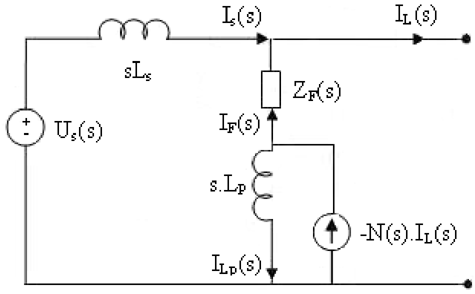


Figure 5. Circuit model of HVDC converter

The Thevenin equivalent circuit of Figure 5 has been illustrated in Figure 6. The equivalent voltage source $U_{eq}(s)$ can be expressed as:

$$U_{eq}(s) = \frac{sL_P + Z_F(s)}{sL_s + sL_P + Z_F(s)} \cdot U_s(s) \quad (5)$$

And equivalent impedance $Z_{eq}(s)$ can be expressed as:

$$Z_{eq}(s) = \frac{(sL_s)(sL_P)(1+N(s))}{sL_s + sL_P + Z_F(s)} + \frac{sL_s \cdot Z_F(s)}{sL_s + sL_P + Z_F(s)} \quad (6)$$

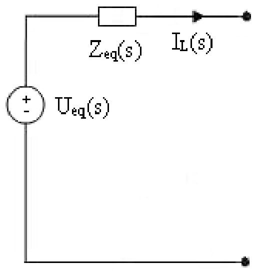


Figure 6. Thevenin equivalent circuit of the HVDC converter station

Equation (5) shows that $U_{eq}(s)$ is independent of $N(s)$, while $U_{eq}(s)$ can be modulated by harmonic voltage source $U_s(s)$, inductance $L_P$, smoothing reactor and passive filter. In fact, if $L_s \cdot 2\pi f_i$ is greater than $|Z_F(j2\pi f_i)|$ and $L_P \cdot 2\pi f_i$ at the harmonic frequency $f_i$, increasing $L_s$ or reducing $|Z_F(j2\pi f_i)|$ and $L_P$ can decrease $U_{eq}(s)$ and eliminate the harmonic current on the DC transmission line. Equation (6) shows that the controlled coefficient $N(s)$ only impresses the $Z_{eq}(s)$. If $N(s)$, $s \cdot L_s$, $s \cdot L_P$ and $Z_F(s)$ satisfy (7) and (8) at $f_i$:

$$|j2\pi f_i \cdot L_s| >> |Z_F(j2\pi f_i)| \text{ and } |j2\pi f_i \cdot L_P| \quad (7)$$

$$|j2\pi f_i \cdot L_P||N(j2\pi f_i)| >> |j2\pi f_i \cdot L_P| \text{ and } |Z_F(j2\pi f_i)| \quad (8)$$

Then Equation (6) can be approximately simplified as:

$$Z_{eq}(j2\pi f_i) \approx j2\pi f_i \cdot L_P \cdot N(j2\pi f_i) \quad (9)$$

So, it is possible to control the $Z_{eq}(s)$ by the filter $F(s)$ and inductance $L_P$ according to Equations (3) and (9). Disregarding the noise, $|Z_{eq}(j2\pi f_i)|$ can be increased by optimal selection of value of $L_P$ and proper design of filter $F(s)$ to eliminate the harmonic at $f_i$. Based on the circuit model shown in Figure 6, different affects of passive filter and ADF are decoupled by Equations (5) and (6) and discussion about ADF will be simple. To validate and prove the Equation (3), according to Figure 4, the harmonic compensating current of passive filter branch can be written as:

$$I_F(s) = -\frac{sL_P N(s) + Z_L(s)}{Z_F(s) + sL_P(1+N(s)) + Z_L(s)} \cdot I_s(s) \quad (10)$$

If $s \cdot L_P N(s)$, $Z_L(s)$ and $Z_F(s)$ satisfy Equations (11) and (12) at $f_i$:

$$|N(j2\pi f_i)| >> 1 \quad (11)$$

$$|j2\pi f_i \cdot L_P||N(j2\pi f_i)| >> |Z_F(j2\pi f_i)| \text{ and } |Z_L(j2\pi f_i)| \quad (12)$$

Then Equation (10) can be approximately simplified as:

$$I_F(s) \approx -I_s(s) \quad (13)$$

Equation (13) approximately is the same Equation (1). So by proper designing of filter $F(s)$ and optimal choice of $L_P$, Equation (1) can be validated. The control method presented in [8], has been applied to control the ADF for elimination of DC transmission line current characteristic harmonics. Its structure and principle of its operation has thoroughly been described in [8]. Based on the theoretical analyses performed in [8], the transfer function of the filter $F(s)$ designed in [8], is expressed as the Equation (14) in this paper.

$$F(s) = \frac{0.00048s}{1+0.006s} \quad (14)$$

Due to switching action of active part of HADF, switching noise is produced on DC transmission line. The noise is also entered into PWM modulating signal $i_{ref}$ through the current $i_L$ and filter $F(s)$. The noise in the PWM modulating signal impresses the work of PWM circuit extremely and impairs the control system operation. Since the modulation frequency is high and according to Figure 4, the harmonic voltage output $U_s(s)$ is short circuit and the resistors and capacitors in the circuit can be ignored. Supposing that the equivalent inductance of HVDC converter and smoothing reactor is $L_1$, the equivalent circuit of passive filter is $L_2$ and the equivalent inductance of DC transmission line and remote load is $L_3$ and DC supply voltage of ADF is $U_d$, in this status, the switching noise amplitude of the PWM modulating signal $i_{ref}$, can be written as:

$$A_{PWMnoise} = \frac{10^{-3} \cdot U_d \cdot |F(j2\pi f_{PWM})|}{(L_2 + L_3 + \frac{L_2 L_3}{L_1}) \cdot 2 f_{PWM}} \quad (15)$$

If all of the dc transmission line current harmonics are eliminated, the modulation index $m_i$, can be expressed as:

$$m_i = \frac{A_{PWM\ noise}}{\text{Peak of carrier wave}} \le 1 \quad (16)$$

If the ADF can operate stably with control method presented in [8], the modulation index will not exceed 1. According to [8], the peak of carrier wave is equal to $1.5\times10^{-7}$. According to Equations (15) and (16), the upper limit of the ADF DC supply voltage $U_d$ can be determined as:

$$U_d \le 3\times10^{-4}(L_2 + L_3 + \frac{L_2 L_3}{L_1}) \cdot f_{PWM} \cdot \frac{1}{|F(j2\pi f_{PWM})|} \quad (17)$$

By defining $m_{i-\min}$ as the lower limit of modulation index, the lower limit of the ADF DC supply voltage can be determined as follows:

$$m_{i-\min} = \frac{1}{\text{upper limit of } U_d} \quad (18)$$

Then

$$m_{i-\min} \le m_i \le 1 \quad (19)$$

So

$$1 \le U_d \le 3\times10^{-4}(L_2 + L_3 + \frac{L_2 L_3}{L_1}) \cdot f_s \cdot \frac{1}{|F(j2\pi f_{PWM})|} \quad (20)$$

According to Equation (20), it is clear that ADF DC supply has very low voltage range so the rated nominal power of the ADF active part has significantly been reduced. First essential stability condition of ADF is inferred from the equivalent circuit shown in Figure 6, when the modulation index is less than 1. The impedance $Z_L(s)$ has the non-negative resistance. So, if the impedance $Z_{eq}(s)$ has positive resistance in the whole frequency band, the HVDC system is stable at each frequency point [8]. In (6), the second item has a non-negative resistance part and the multiplier $sL_s/(sL_s + sL_P + Z_F(s))$ in first item has a phase characteristic close to $0^\circ$ in the harmonic frequency range.

According to Equation (3), only when the phase characteristic of the filter $F(s)$ is limited in the range $0^\circ \sim 90^\circ$, $Z_{eq}(s)$ satisfies the positive resistance necessity and the stable control system will be acquired. According to Equation (14), the filter $F(s)$ is a high-pass filter and filters the DC component of DC transmission line current and its AC component which contains the harmonics, is obtained. According to Equations (2) and (4) and Figure 3, with applying the control method mentioned in [8], the DC transmission line current $i_L$ with minus sign is applied to the filter $F(s)$ then the filtered current which includes the harmonics of DC transmission line current is entered to the PWM program as the PWM modulating signal $i_{ref}$. The PWM circuit generates a pair of complementary signals to control the single-phase full-bridge inverter which is the active part of HADF. The phase response of $F(s)$ is limited in $[0^\circ, 90^\circ]$.

## III. SIMULATION RESULTS

In order to simulation of HVDC system with HADF for harmonic suppression of DC transmission line current, the PSCAD/EMTDC software package has been utilized. For implementation of HVDC system in this software, the equivalent circuit shown in Figure 4 is applied. A 12-pulse fully controlled rectifier is used [4] as the HVDC converter. The line voltage of the ac input is 295 (V) [4], the firing angle is 45° and the output voltage of the 12-pulse rectifier is 276 (V). The value of smoothing reactor is 0.2 (H).

The passive filter adopts 730.62 (Hz) singe-tuned filter. The values of passive filter parameters are: $C_F$ = 9.5 (μF), $L_F$ = 5 (mH). The value of inductance $L_P$ is 0.01 (H). Supposing that filtering equipments in inverter side have ideal effects, the dc transmission line and inverter can be considered as the load impedance $Z_L(s)$ in Figure 4.

The Figure (7) shows the load circuit implemented by PSCAD/EMTDC. In this circuit, a T-type equivalent circuit is utilized to simulate DC transmission line. Because of system symmetry, a 0.2 H smoothing reactor is in inverter side. The passive filter in inverter side shown in Figure 7, absorbs most of the harmonics generated by the inverter so the inverter is replaced with a 75 Ω resistor to simplify the simulation. The single-phase full-bridge inverter which is the active part of HADF has four IGBT switches. The voltage of ADF DC Supply $U_d$ is selected 3 V under the restriction of Equations (17) and (20). The lower and upper limit of $U_d$ is 1 and 3.375 V respectively. The selection range of $U_d$ is very low and hence according to Equation (15), the switching noise has very low amplitude. The frequency of carrier wave is equal to 16 kHz. The Figure 8 shows obviously a comparison between following currents:

Current $i_s(t)$ is the current generated by HVDC converter, current $i_{L-pf}(t)$ is the DC transmission current only when single-tuned passive filter works and without ADF and current $i_L(t)$ is the DC transmission line current when the ADF is working.

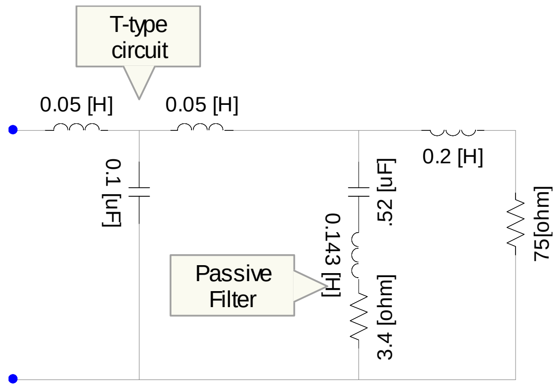


Figure 7. Load circuit implemented by PSCAD/EMTDC

According to Figure 8, the harmonic elimination power of the ADF is very significant. The Table 1 shows the RMS values of the DC transmission line current harmonics when the modified configuration of the HADF works. The compensating efficiency can be defined as:

$$\eta_n = (1 - \frac{I_{Ln}}{I_{Sn}}) \times 100 \quad (21)$$

Where $I_{Ln}$ is the RMS value of DC transmission line current harmonic and $I_{Sn}$ is the RMS value of harmonic of current $i_s$ and $n$ is the harmonic order equal to 12, 24, 36, and 48. Table 2 shows compensating efficiency when ADF is working and shows that harmonic compensation effect of modified configuration of HADF is very significant.

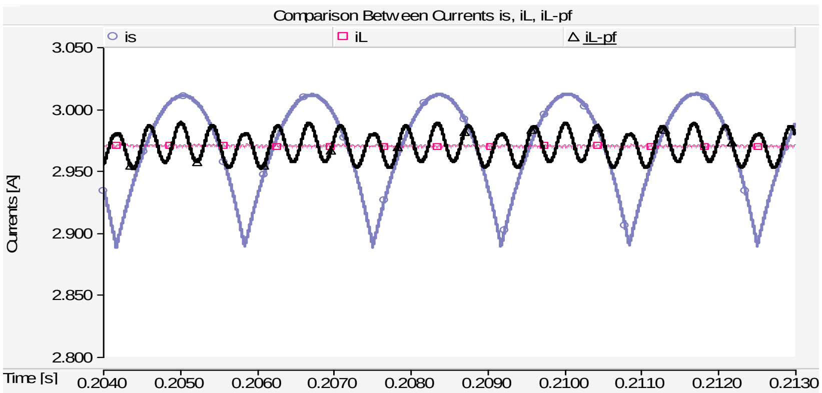


Figure 8. Comparison between currents $i_s$, $i_L$, $i_{L-pf}$

Table 1. RMS values of DC transmission line current harmonics

| Harmonic orders | RMS values of the DC transmission line current harmonics (mA) |
|---|---|
| | ADF is working |
| 12 | 0.154 |
| 24 | 0.056 |
| 36 | 0.05 |

Table 2. Compensating efficiency

| Efficiency | $\eta_{12}$ | $\eta_{24}$ | $\eta_{36}$ | $\eta_{48}$ |
|---|---|---|---|---|
| ADF is working | 99.6% | 99.3% | 98.7% | 96.9% |

## IV. CONCLUSIONS

In this paper a modified configuration of hybrid active DC filter was proposed in HVDC transmission system for harmonics elimination of DC transmission line current. Due to Thevenin equivalent circuit, different affects of single-tuned passive filter and hybrid ADF are decoupled. Five key problems in hybrid ADF design containing the choice of ADF dc supply voltage range, adjustment of modulation index, stability conditions, switching noise disturbance and filter design to obtain harmonics, are solved by the Thevenin equivalent circuit. Reduction of nominal power of ADF active part, very low DC supply voltage, elimination of coupling transformer and very small switching noise amplitude, are the major advantages of modified configuration of the hybrid active DC filter.

With selection of optimal values for inductances $L_F$ and $L_P$, changes of the DC transmission line and remote load have no effect on the HADF system. A very important advantage of modified ADF configuration is the its ability in regulation of nominal voltage-current of ADF active part (with optimum selection of its passive elements) which has the most effect on prime cost of ADF. The theoretical analysis and simulation results prove and validate the accuracy of aforementioned claims.

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## BIOGRAPHIES

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