

# APPLICATION OF A 5 MVA, 4.16 kV D-STATCOM SYSTEM FOR VOLTAGE FLICKER COMPENSATION AT SEATTLE IRON & METALS

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## ABSTRACT

The installation and of a 5 MVA, 4.16 kV Distribution-level Static Reactive Compensator (D-STATCOM) was completed in July, 1999 at the Seattle Iron & Metals Corporation's new steel recycling facility in Seattle, Washington. The D-STATCOM technology was selected as the preferred option for voltage flicker compensation of a 4,000 Hp shredder motor, which will be operated at the new facility. For voltage flicker applications, the D-STATCOM technology provides rapid-response compensation to correct for the voltage fluctuation characteristics imposed on the interconnected system during the shredder motor operation. In this application, the D-STATCOM System will be operating at 4.16 kV and will provide reliable power quality for both the new steel recycling facility and the interconnecting utility, Seattle City Light, which provides power to the plant at 26.4 kV. Final field testing and commissioning of the D-STATCOM System was completed in February, 2000.

**Key Words** – D-STATCOM, Custom Power, Power Quality, Voltage Source Inverter, Voltage Sourced Converter, Voltage Compensator System, Static Voltage Compensation, Voltage Flicker Compensation, Shredder Motor

## 1. INTRODUCTION

This paper describes the application of the D-STATCOM technology, along with system specifications in relation to the Seattle City Light distribution system requirements, the shredder motor characteristics, and the design configuration and performance criteria of the D-STATCOM voltage compensation system. The major items with respect to the D-STATCOM System application addressed in this paper include:

- System description and specifications
- Circuit design and basic configuration
- Control system design and specifications
- Performance specification and flicker analysis
- Determination of D-STATCOM System capacity

The D-STATCOM technology, which consists of an IGBT-based voltage source inverter system, uses advanced power electronics to provide voltage stabilization, flicker suppression, power factor correction, harmonic control, and a host of other power quality solutions for both utility and industrial applications.

## 2. D-STATCOM SYSTEM DESCRIPTION

### 2.1 System Outline:

A single line diagram of the D-STATCOM System for the Seattle Iron & Metals Corporation application is shown in Figure 1. The system essentially consists of a set of inverters, main transformer, and a capacitor & reactor bank. The inverters have a rated output capacity of +/-2,000 KVAR (continuous rating) and +/-3,000 KVAR (overload rating for 1 minute). The system is

designed such that it can control the reactive power from 0 to 5,000 kVAr in combination with the inverters and the capacitor banks used for both the shredder motor and the D-STATCOM System.

The inverters are connected to the secondary side of the main transformer. The main transformer is used for stepping the voltage of 4.16kV down to 300V, which is the suitable voltage for the inverter operation.

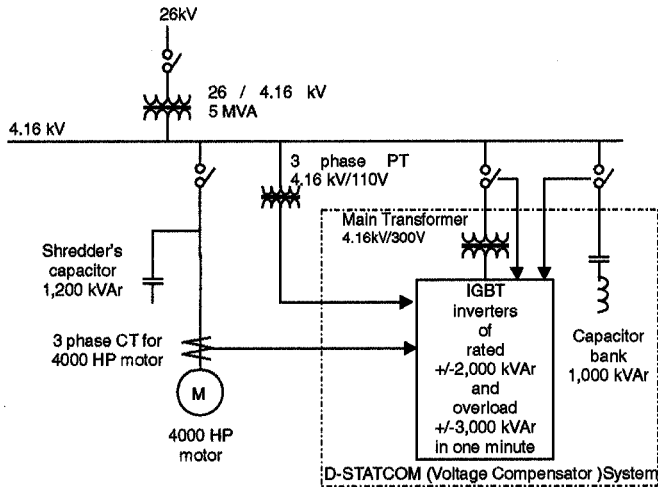


Figure 1 - Single-Line Diagram of 5 MVA, 4.16 kV D-STATCOM System

## 2.2 Inverter Design:

The inverter equipment consists of 5 sets of inverter units as shown in Figure 2. Each inverter unit has a separator switch and local control. One of the inverter units contains a system controller which is the master control of the D-STATCOM System (or Voltage Compensator System). Each inverter unit is a voltage source type inverter and has a rated capacity of 400 kVAr (continuous rating) and overload capacity of 600 kVAr for one minute. Thus, the five inverters can output 2,000 KVAR continuously and 3,000 KVAR as an overload rating for 1 minute in total. The inverters are designed with a redundancy such that even though one of the inverter units is out of service, the remaining 4 inverters can maintain operation with 80% of full rating. This is done by separating the failed inverter unit from the circuit with the separator switch.

The use of sophisticated semiconductor devices, Insulated Gate Bipolar Transistors (IGBT's), are applied in the inverter design. The ratings of the IGBT elements are 1,200 V, 600 A.

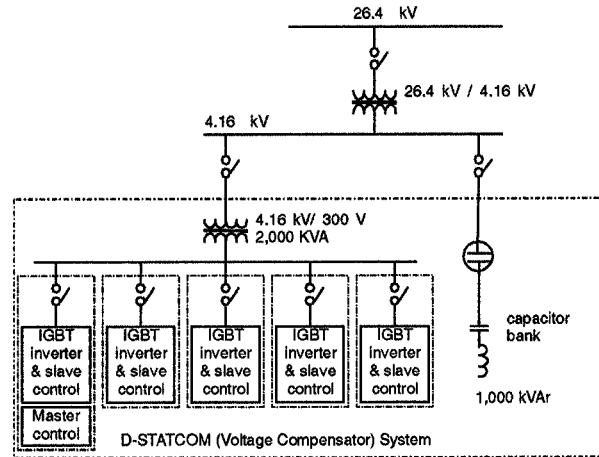


Figure 2 - Configuration of the D-STATCOM System (IGBT-based Inverter Design)

## 2.3 Main Transformer:

The main transformer is used for stepping the voltage of 4.16 kV down to 300 V, the suitable voltage for the inverter output. The transformer is an oil-immersed type unit with natural air cooling. The transformer is installed outdoors adjacent to the inverter housing. The connection between the transformer and the inverters will be made by cables, and the connection between the primary terminals of the transformer and the high-voltage switchgear is also made by cables.

## 2.4 Capacitor Bank:

The capacitor bank has a rated capacity of 1,000 kVAr. It consists of one set of capacitor units, a series reactor and a vacuum switch. These components of the capacitor bank are assembled in one compact package, together with the necessary control and protection equipment. The capacitor bank is designed for outdoor use. The connection between the capacitor bank and the high-voltage switch-gear is made by cables.

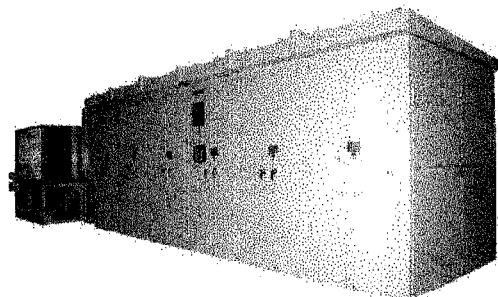


Figure 3 - External View of 5MVA D-STATCOM System

## 2.5 System Control:

Figure 4 shows a block diagram of the control scheme for the D-STATCOM System. The shredder motor current is detected by a CT in the shredder motor circuit, and the detected current signal is transmitted as an input to the master control circuit. The 4.16 kV voltage is detected by a PT on the 4.16 kV bus-bar and the detected voltage signal is transmitted as an input to the master control circuit. In the master control circuit, reactive power of the shredder motor load is calculated by means of a p-q conversion method. Additionally, a current reference signal for the inverter is calculated in a current reference controller. The calculated reference signal is supplied to the slave controller of each inverter. In each inverter unit, the slave controller controls the inverter output current in response to the current reference signal, independently.

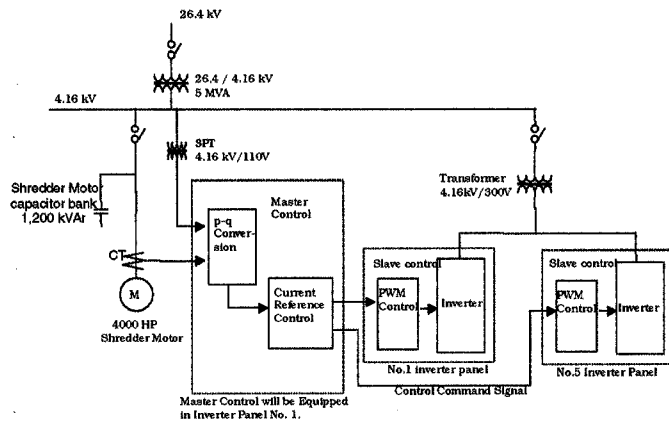


Figure 4 - Control Block Diagram of D-STATCOM System

## 2.6 Starting/Stopping Operation:

**Starting Method:** Starting of the D-STATCOM System is easily performed from the operator display panel in the housing, or from the customer's remote control panel. The necessary sequence operation for starting can be made automatically by a single touch on the starting button in the panel. After the completion of the starting operation, the D-STATCOM System begins its compensation function automatically.

**Stopping Method:** Stopping of the D-STATCOM System is also easily performed from the operator display panel in the housing, or from the customer's remote control panel. The necessary sequence operation for stopping can be made automatically by a single touch on the stopping button in the panel.

## 3. D-STATCOM SYSTEM PERFORMANCE SPECIFICATION and FLICKER ANALYSIS

### 3.1 Performance Conditions:

The performance specification of the D-STATCOM System was originally based on data provided by Seattle Iron & Metals for the shredder motor characteristics, and by Seattle City Light for the 26.4 kV distribution supply network characteristics.

### 3.2 System Configuration for Analysis:

The system configuration of Figure 5 was considered for the initial performance specifications and voltage flicker analysis of the D-STATCOM System.

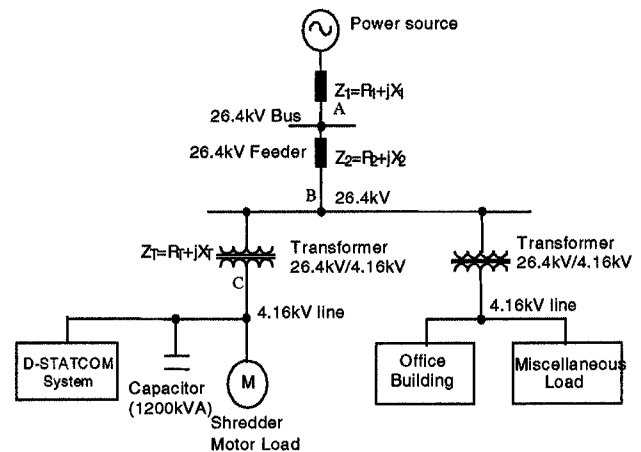


Figure 5 - System Configuration for Performance Specification and Voltage Flicker Analysis

Two supply substations from Seattle City Light's 26.4 kV distribution network were considered in the design analysis – South Substation and Duwamish Substation. The source impedance ( $Z_1$ ) and feed impedance ( $Z_2$ ) for each station supply, and the 5 MVA supply transformer impedance ( $Z_T$ ), are as follows:

- (1) 26.4 kV Source Impedance:  $Z_1$  (on 100 MVA base)  
 South:  $Z_{s0} = 0.0022 + j0.1309$  (pu)  
 Duwamish:  $Z_{du} = 0.00298 + j0.1154$  (pu)  
 Note:  $Z_1$  is with one supply bank out of service (N-1), which provides a minimum flicker impact condition.
- (2) 26.4 kV Feeder Impedance:  $Z_2$  (on 100 MVA base)  
 South F2628:  $Z_{2628} = 0.0556 + j0.2634$  (pu)  
 Duwamish F2683:  $Z_{2683} = 0.0414 + j0.1483$  (pu)
- (3) Transformer Impedance:  $Z_T$   
 $\%Z = 5.5\%$  (5000kVA base),  $X/R = 10$   
 $Z_T = 0.11 + j1.1$  (pu) on 100MVA base

### 3.3 Specification of Voltage Fluctuation:

Table 1 and Figure 6 provide the specification of the load fluctuation profile and flicker limit. The shredder motor load is to be operated within the maximum torque (i.e., not more than  $s=0.022$ ). The maximum torque is caused at  $s=0.022$  which is obtained from the shredder motor equivalent circuit of Figure 7.

The voltage fluctuation caused by connected loads other than the shredder, and the voltage fluctuation which exists on the power system, are not considered in this particular evaluation.

Table 1 - Load Fluctuation Profile and Flicker Limit

No.	Load Condition	Load Current	Fluctuation Frequency	Upper Limit of $\Delta V$
1	200% load	2 x FLA	1 hit /hour	2.7%
2	175% load	1.75 x FLA	10 hits /hour	1.1%
3	150% load	1.5 x FLA	20 hits /hour	0.9%
4	100% load	1.0 x FLA	20 hits/hour	0.9%
5	50% load	0.5 x FLA	1 hits / minute	0.7%
6	25% load	0.25 x FLA	5 hits / minute	0.5%

Note: FLA : Current at Load=1pu (= 450A)

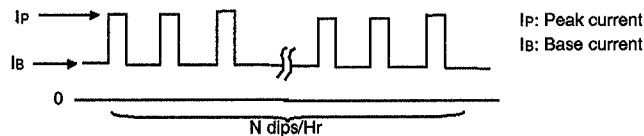


Figure 6 - Load Fluctuation Profile

### 3.4 Load Characteristics:

The shredder motor characteristics are represented in the equivalent circuit of Figure 7.

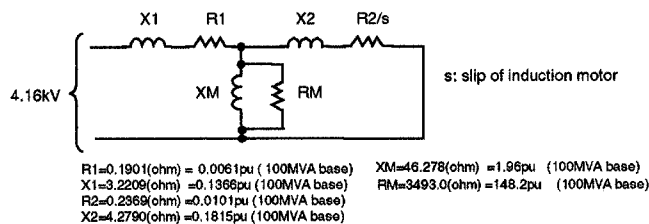


Figure 7 - Equivalent Circuit of the Shredder Motor

### 3.5 Point of Common Coupling:

The Point of Common Coupling (PCC) for evaluating the voltage fluctuation is on the 4.16 kV bus on the low voltage side of the system supply transformer (5 MVA, 26.4kV / 4.16kV transformer), i.e., point C in Figure 5.

### 3.6 Measurement of Voltage Fluctuation:

Measurement of the voltage fluctuation is made at point C in Figure 5. The measurement circuit is shown in Figure 8. The measurement is made to detect the voltage on the 4.16kV bus through a PT, and the rms value of the line-to-line voltage of one phase is measured with a voltage transducer.

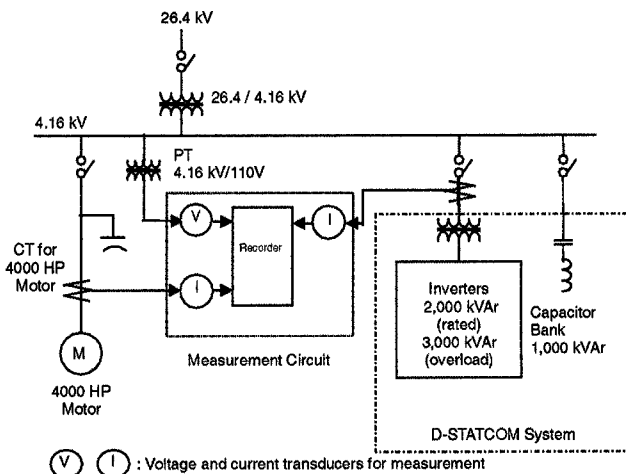


Figure 8 - Measurement Circuit

### 3.7 Evaluation Method of Voltage Fluctuation:

Voltage fluctuation on the 4.16 kV bus is evaluated from a recorded oscillograph chart. The voltage fluctuation is plotted as shown in Figure 9, with an indication for the number of voltage dips.

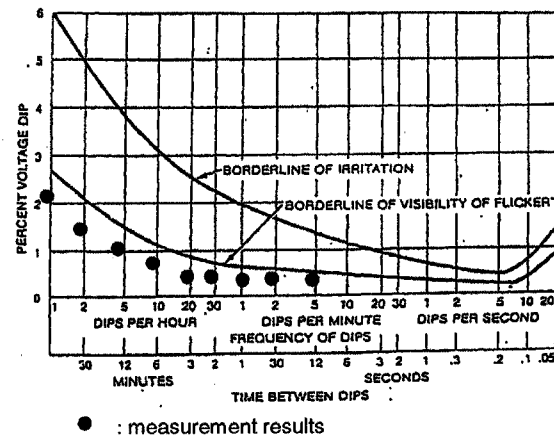


Figure 9 - Method for Evaluating Voltage Fluctuation

### 3.8 Performance Analysis of D-STATCOM System

#### 3.8.1 Load Conditions

The load conditions for the analysis are as follows:

- 1) Induction motor characteristics:
  - (a) Rated voltage : 4.16 kV
  - (b) Rated output : 4000 HP
  - (c) No. of poles: P=14
  - (d) Type of motor: Wound rotor motor
  - (e) Frequency: 60 Hz
  - (f) Starting current: 450 A
- 2) Shredder motor characteristics:
  - (a) Equivalent circuit of shredder motor: The equivalent circuit of shredder motor is represented as in Figure 7 of Section 3.4.
  - (b) Load Characteristics:
 

The following load characteristics are used according to the characteristics provided by Seattle Iron & Metals for the motor data:

##### FULL SPEED

Load (p.u)	1.	0.75	0.5
Speed(rpm)	509.7	511	512.1
Stator Current(A)	590.9	472.0	376.6
Efficiency(%)	96.7	96.8	96.5
Power factor	0.725	0.675	0.565

##### (c) Performance:

Standstill open-circuit voltage b/tw rings: 2060V  
 Full Load Rotor Current: 890A  
 Full load power =  $1.732 \times 2060 \times 890 = 3175\text{kW}$

- 3) Motor Output Power vs. Motor Speed Curve:  
 The motor output power vs. motor speed curve of Figure 10 is used for the analysis.

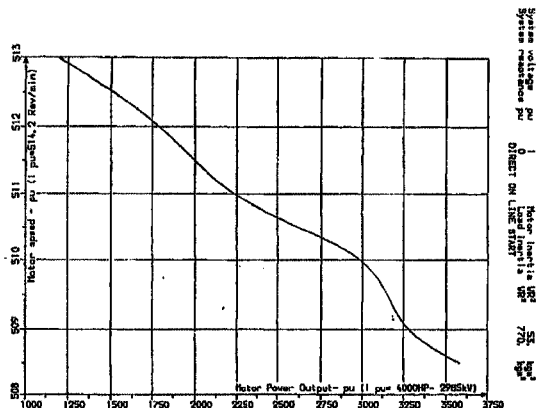


Figure 10 - Load Characteristic: Motor Output vs. Speed Curve

- 4) Motor Operation Characteristics:  
 The shredder motor load is operated within maximum torque ( i.e., less than  $s=0.022$ ). And, the locked rotor condition ( $s=1$ ) is not considered.  
 (Note: Maximum torque is caused at  $s=0.022$  which is obtained from the shredder motor equivalent circuit of Figure 7).

#### 3.8.2 Load Fluctuation Profile and Upper-Limit Level of Flicker

- 1) Flicker Upper-Limit: The Flicker borderline is specified in accordance with IEEE Std 1250-1995, as shown in Figure 9 of Section 3.7.

- 2) Specified load fluctuation profile: The load fluctuation profile is specified as follows:

Motor starting: Twice daily, 8 a.m. and Noon. The starting current is 450A.

Load fluctuation profile: The Motor is assumed to be operated within the stable region (within maximum torque) and with the following load fluctuation profile, which is shown graphically in Figure 6 of Section 3.3.

- (a) 200% load : less than once per hour
- (b) 175% load : 10 times per hour
- (c) 150% load : 20 times per hour
- (d) 100%load : 20 times per hour
- (e) 50% load : less than once per minute
- (f) 25% load : less than five times minute

- 3) Specification of load fluctuation and flicker upper-limit: Considering the load fluctuation profile specified above and the flicker upper-limit as specified in Figure 8, the specification of load fluctuation and flicker upper-limit used for the analysis can be summarized in Table 1 of Section 3.3.

### 3.9 Analysis of Voltage Fluctuations and Required Compensation Capacity

#### 3.9.1 Voltage Drop without Compensation

On the basis of the conditions provided, the voltage fluctuation without compensation can be calculated as shown in Table 2.

**Table 2 - Voltage Fluctuation (%) w/out Compensation**

	200% FLA			175%FLA			150%FLA		
	26kVBUS	TRF-H	TRF-X	26kVBUS	TRF-H	TRF-X	26kVBUS	TRF-H	TRF-X
South F-2628	0.67	2.21	8.10	0.53	1.77	6.44	0.44	1.50	5.44
Duwamish F-2683	0.60	1.50	7.94	0.47	1.21	6.31	0.39	1.03	5.33

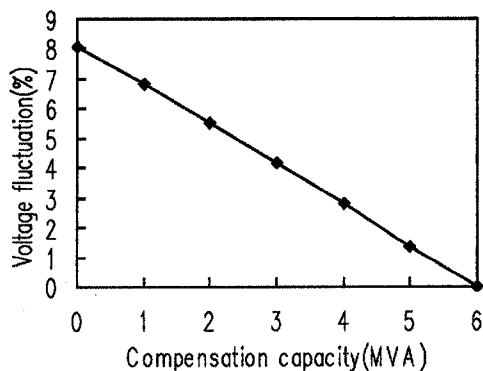
	100% FLA			75%FLA			50%FLA		
	26kVBUS	TRF-H	TRF-X	26kVBUS	TRF-H	TRF-X	26kVBUS	TRF-H	TRF-X
South F-2628	0.30	1.02	3.68	0.23	0.79	2.89	0.19	0.61	2.26
Duwamish F-2683	0.26	0.70	3.60	0.21	0.54	2.83	0.16	0.42	2.22

Note: TRF-H and TRF-X refer to the primary and secondary side of the supply transformer, respectively

From Table 2, it is obvious that the most severe case is the supply from South Feeder F2632. Therefore, the analysis for the case of South Feeder F-2628 is sufficient in order to determine the necessary capacity of the D-STATCOM System.

### 3.9.2 Determination of D-STATCOM System Size

The most critical case to evaluate in determining the size of the D-STATCOM System is for the case of 200% load. The calculation results, in terms of the relation between voltage fluctuations and compensation capacity at 200% load, are summarized in the chart of Figure 11. From Figure 10, the necessary capacity of the D-STATCOM System is determined to be 5 MVA, in order to reduce the flicker level within the specified limit of 2.7% on the secondary terminal of the transformer.



**Figure 11 - Voltage Fluctuation on the Transformer Primary Terminal**

### 3.9.3 Voltage Fluctuation with D-STATCOM

The voltage fluctuations with a 5 MVA D-STATCOM System are summarized in Table 3 for each load pattern. For each fluctuation pattern, the voltage fluctuation is reduced within the limits specified by application of the D-STATCOM System.

**Table 3 - Voltage Fluctuation (%) with Compensation**

	200%FLA			175%FLA			150%FLA		
	26kVBUS	TRF-H	TRF-X	26kVBUS	TRF-H	TRF-X	26kVBUS	TRF-H	TRF-X
South F-2628	0.07	0.43	1.26	0.03	0.30	0.81	0.02	0.23	0.56
Duwamish F-2683	0.07	0.31	1.23	0.03	0.22	0.72	0.01	0.15	0.40
Specified Limit	2.7%			1.1%			0.9%		

	100%FLA			75%FLA			50%FLA		
	26kVBUS	TRF-H	TRF-X	26kVBUS	TRF-H	TRF-X	26kVBUS	TRF-H	TRF-X
South F-2628	0.01	0.16	0.40	0.01	0.11	0.29	0.01	0.08	0.23
Duwamish F-2683	0.01	0.12	0.36	0.01	0.10	0.28	0.01	0.07	0.22
Specified Limit	0.9%			0.7%			0.5%		

### 3.9.4 Capacity of D-STATCOM System

From above analysis, the required capacity of the D-STATCOM System is determined to be as follows:

$$\text{Capacity of D-STATCOM System} = 5 \text{ MVA at } 4.16 \text{ kV}$$

## 4. CONCLUSIONS

A 5 MVA, 4.16 kV D-STATCOM System has been specified and designed to provide voltage flicker compensation for a 4,000 Hp shredder motor at Seattle Iron & Metals Corporation. The D-STATCOM System design, capacity, and performance criteria are determined by a detailed analysis using supply system data from Seattle City Light and the shredder motor characteristics.

Operation of the D-STATCOM System provides an advanced, high-speed control technology for reactive power compensation in order to provide voltage flicker compensation, voltage stabilization, power factor control, and other distribution system mitigation measures for power quality improvement.

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## 6. BIOGRAPHIES

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