Ferroresonance Conditions Associated With a 13 kV Voltage Regulator During Back-feed Conditions

D. Shoup, J. Paserba, A. Mannarino

Abstract-- This paper describes ferroresonance conditions for a 13 kV feeder circuit with a voltage regulator connected under back-feed conditions, where high overvoltages developed causing the failure of distribution class surge arresters. Key parameters of equipment and circuit conditions are described that lead to zero sequence, i.e., 3rd harmonic, resonance conditions where the only path for the magnetizing current of a voltage regulator to flow is through the capacitance of connected cable circuits, isolated from the rest of the system by delta-wye connected network transformers. The results of the study provide guidance for the identification of potential ferroresonance circuits in distribution systems and potential means of mitigation through the application of grounding transformers, modification to protective relaying strategies, and consideration to circuit connectivity.

Keywords: ferroresonance, distribution, back-feed, voltage regulator, network transformers, resonance, grounding transformer, protective relaying

I. INTRODUCTION

FERRORESONANCE conditions are described for a 13 kV feeder circuit where a voltage regulator is left connected to cables under back-feed conditions. System conditions, key equipment parameters, and means of overvoltage mitigation are described to avoid high overvoltages that could cause the failure of distribution class surge arresters. The focus is on zero sequence, i.e., 3rd harmonic, resonance conditions, where the only path for the magnetizing current of a voltage regulator to flow is through the capacitance of connected cable circuits, isolated from the rest of the system by delta-wye connected network transformers.

The study provides guidance for the identification of potential ferroresonance circuits in distribution systems, recognition of key equipment parameters, and potential means of mitigation through the application of grounding transformers, modification to protective relaying strategies, and consideration to circuit connectivity.

II. SYSTEM TOPOLOGY REPRESENTATION

Fig. 1 shows the representation of the distribution system, where the 13 kV system is of focus. The 230 kV system is represented by its positive and zero short-circuit strength on the high-side of a 230/13.2 kV Delta-Wye step-down transformer. On the low-side of the transformer three radial 13 kV feeder circuits are represented in both positive and zero sequence, each consisting of the following:

- Station breaker
- 4 miles of mostly overhead wire circuit with ~4000 ft of underground cable
- 1.2 (3-400 kVar) Mvar capacitor bank
- Voltage regulator capable of carrying load of 10 MVA (3-333 MVA)
- Sectionalizer at load-side of regulators
- 1.2 miles of cable circuit
- 10 MVA of Delta-Wye connected network transformers
- Network protectors at low-side of network transformers

Two different circuit configurations for the station breaker were examined. One was examined with the breaker on the source-side of the voltage regulator near its terminals as shown in Fig. 1 for the far right 13 kV feeder circuit. A second configuration, with the station breaker before the 4 miles of overhead wire and underground cable circuit, as shown for the two other feeder circuits, was also examined. Ferroresonance conditions were observed for either configuration under back-feed conditions.

The back-feed conditions of interest here were based on an actual system condition where the station breaker was open and a network protector stuck closed at the low-side of a network protector, with the sectionalizers closed. For this system condition, the 1.2 miles of cable circuit and voltage regulator is back-fed through the network transformer adjacent to the stuck network protector. Note that the load at the low-side of the network transformers is not included here since it does not impact the floating back-feed circuit of interest here.

The focus of the analysis described here is on the interaction that occurs between the 1.2 miles of cable circuit and voltage regulator, and potential means of mitigation for all potential overvoltage conditions.

III. KEY EQUIPMENT REPRESENTATION

The following describes the representation of key equipment of Fig. 1 for the Electromagnetic Transients Program (EMTP) for the ferroresonance back-feed analysis. EMTP representation of the following equipment is described: voltage regulator, grounding transformer, surge arresters, cables, overhead wire, and network transformers.

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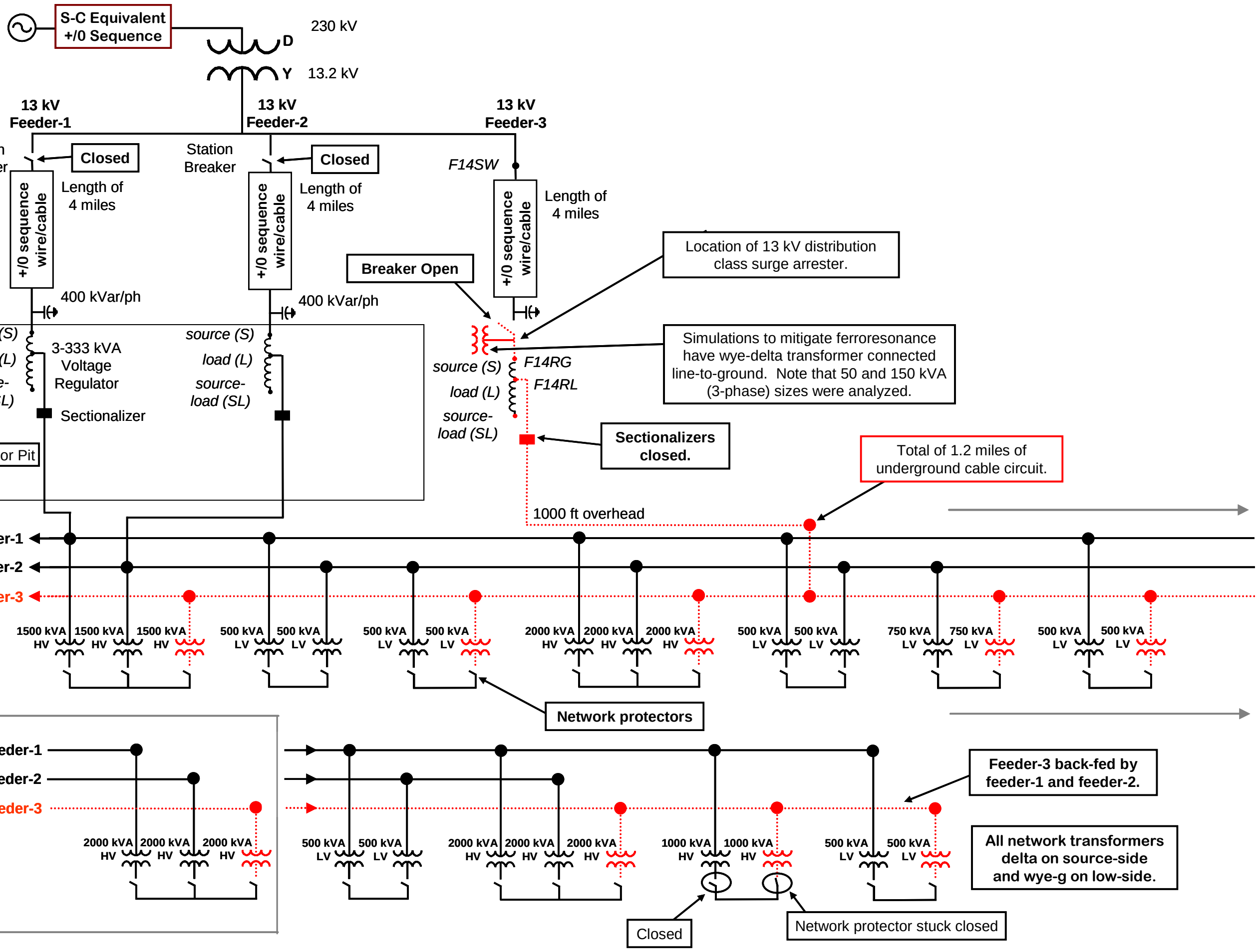

Fig. 1. One-line diagram of back-feed circuit under analysis.

A. Voltage Regulator

The voltage regulator with a through-put capability of 10 MVA, rated as 1 MVA based on series winding, was represented with the following characteristics:

- Magnetizing reactance of 3.2 H
- Saturated reactance of 14 mH

An EMTP type 98 nonlinear reactor was used to represent the excitation characteristics of the voltage regulator, shown in Fig. 2a and 2b. [1-5]

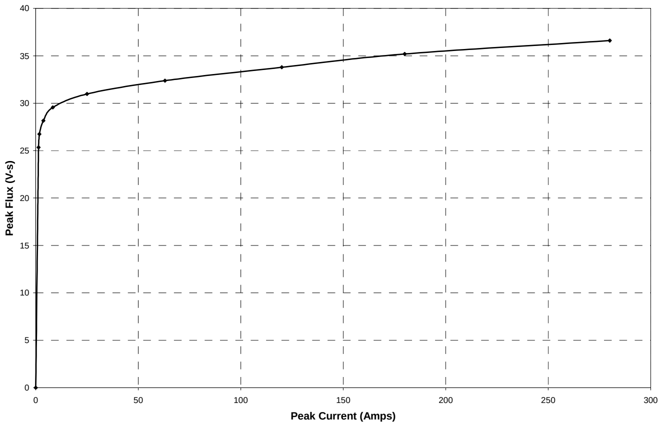

Fig. 2a. Voltage regulator saturation characteristics.

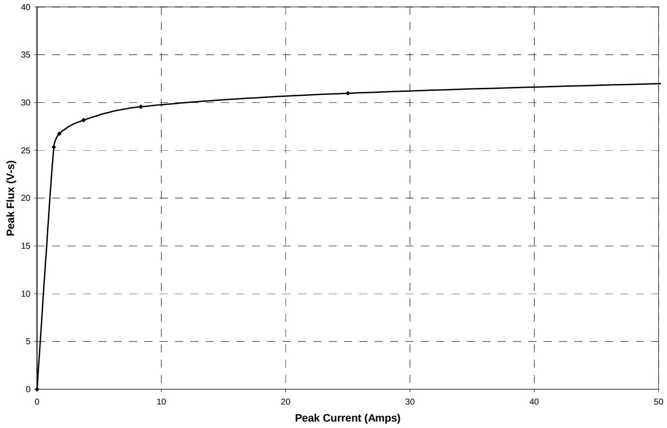

Fig. 2b. Zoom of voltage regulator saturation characteristics.

B. Grounding Transformer

The EMTP classical "transformer" representation was used to represent the grounding transformer, based on its MVA size, winding voltages, winding connectivity, and leakage impedance. The grounding transformer was specified as a wye-delta connected transformer with 3-phase MVA ratings of 50 kVA and 150 kVA examined, each based on a leakage impedance of 10%. For the 13 kV wye-connected winding, the leakage impedance is 338 Ω or 0.9 H for the 50 kVA transformer and 113 Ω or 0.3 H for the 150 kVA transformer. [1, 6-8]

C. Distribution Class Surge Arrester

The 13 kV class distribution class surge arresters were modeled using an EMTP type 92 piece-wise linear representation [1, 5]. The arresters were specified with a 10 kV rated duty cycle, 8.4 kV rated maximum continuous operating voltage (MCOV), and energy duty absorption capability of 4.9 kJ/kV based on the MCOV, or 4.9 kJ/kV x 8.4 kV = 41 kJ.

Surge arresters were modeled based on manufacturer's minimum characteristics for a slow wave front appropriate for estimating peak energy duty for screening purposes. Simulations where significant energy duty applied was imposed on arresters were flagged.

TABLE 1
DISTRIBUTION CLASS SURGE ARRESTER CHARACTERISTICS

Voltage Where Arrester Applied:	**13 kV**	
Rated Duty Cycle (kV):	10	
Rated MCOV (kV):	8.4	
Base for V-I Characteristics (kV) :	26.8	
Energy Duty Absorption (kJ/kV of MCOV):	4.9	Total kJ: 4.9 x 8.4 = 41 kJ
Surge Arrester V-I Characteristics for Peak Energy Duty		
Current (A, pk)	**Voltage For Energy Duty Model (P.U. on 26.8 kV)**	**Voltage For Energy Duty Model (kV, pk)**
1	0.596	15.973
10	0.631	16.911
100	0.676	18.117
500	0.738	19.778
1000	0.769	20.609
2000	0.807	21.628

D. Cables, Overhead Wire, and Network Transformers

The 1.2 mile of cable circuit was composed of cables of the following averaged characteristics:

- Length: 625 ft
- 3-phase kVar/1000 ft: 7.7 kVar
- Surge impedance: 36 Ω
- Resistance: 0.5 Ω/mi
- Inductance: 750 μH/mi

The total capacitance for the feeder-3 back-fed circuit was 0.777 μF for the 1.2 mi section, which is the capacitance that interacted with the saturation characteristics of the voltage regulator under analysis here.

The overhead sections were composed of the following average characteristics: length of 3000 ft sections, resistance of 0.045 Ω/1000 ft, reactance of 0.1 Ω/1000 ft, and charging of 0.2 kVar/1000 ft (3-phase).

The network transformers were all delta-connected on the 13 kV side and wye-grounded connected on the low voltage side, with voltages of 480 V and 216 V, and leakage impedances of 5% to 7%. The 3-phase MVA rating of the transformers ranged from 0.5 MVA to 2.0 MVA.

IV. BACK-FEED ANALYSIS

Simulations were performed for the back-feed case shown in Fig. 1 with no grounding transformer or surge arresters modeled. Fig. 3 shows the line-to-ground voltage at the regulator for the back-feed conditions where the magnetizing current of the regulator flows through the cable circuit, as energy is exchanged between the voltage regulator (saturating nonlinear inductance) and cable circuit (capacitance based on Mvar charging. High voltages, primarily composed of the 3rd harmonic (i.e., 180 Hz), between 3.0 to 4.0 P.U. on a 13 kV system peak line-to-ground voltage base of 10614.5 V.

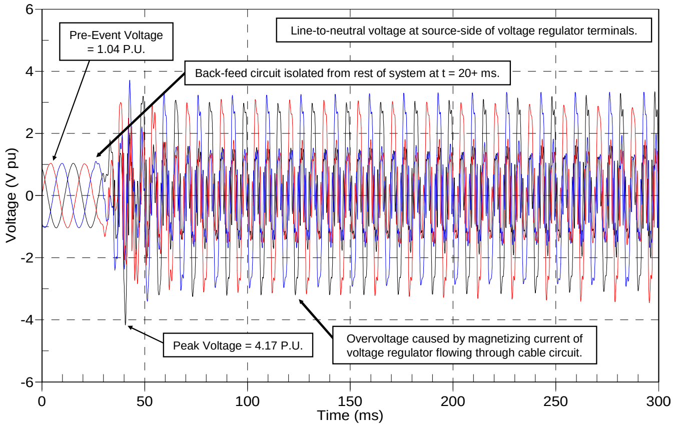

Fig. 3. Line-to-ground voltage at regulator under back-feed conditions without mitigation.

Fig. 4 shows a zoom-in of the saturated current flowing through the voltage regulator for the back-feed circuit under the conditions described for Fig. 3.

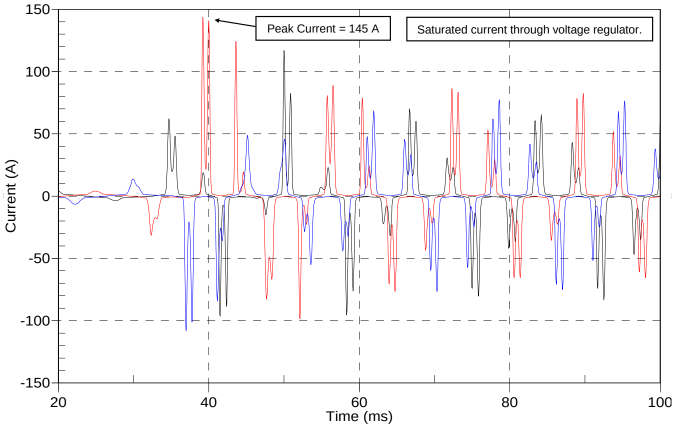

Fig. 4. Saturated current through regulator under back-feed conditions without mitigation.

Tables 2 and 3 list the harmonic summary of the voltage shown in Fig. 3. and the current shown in Fig. 4., respectively. Tables 2 and 3 show that the voltage and current are largely dominated by the 3rd harmonic. [9]

TABLE 2

HARMONIC SUMMARY OF LINE-TO-GROUND VOLTAGE AT REGULATOR

Name	Freq	Fund	% THD	% RMS	RMSh	RMS	ASUM	H3	H5	H7	H9	H11	H13	H15
F14RGA	60	7322	**202**	231	14825	16924	99262	13779	800	172	263	159	182	138
F14RGB	60	7542	**196**	225	14777	16989	112351	13744	356	58	220	66	309	296
F14RGC	60	7447	**198**	227	14751	16898	106411	13753	976	152	66	98	348	213

% THD = Percent Total Harmonic Distortion = RMSh/Fund x 100
% RMS = Percent of Root Mean Square Value = RMS/Fund x100
RMSh = Root Mean Square Value of Harmonic Content
RMS = Root Mean Square Value
ASUM = Arithmetic Sum of All Harmonics
H3-H15 = Magnitude content of each odd harmonic

TABLE 3

HARMONIC SUMMARY OF SATURATED CURRENT THROUGH REGULATOR

Name	Freq	Fund	% THD	% RMS	RMSh	RMS	ASUM	H3	H5	H7	H9	H11	H13	H15
F14RGA	60	10.6	**169**	206	17.9	21.8	263	12.0	4.0	0.59	0.31	0.19	0.11	0.23
F14RGB	60	11.2	**164**	205	18.3	23.0	269	12.4	4.6	0.15	0.46	0.23	0.27	0.64
F14RGC	60	10.7	**168**	204	18.0	21.8	222	12.2	3.8	0.35	0.23	0.20	0.36	0.40

% THD = Percent Total Harmonic Distortion = RMSh/Fund x 100
% RMS = Percent of Root Mean Square Value = RMS/Fund x100
RMSh = Root Mean Square Value of Harmonic Content
RMS = Root Mean Square Value
ASUM = Arithmetic Sum of All Harmonics
H3-H25 = Magnitude content of each odd harmonic

Simulations were repeated with a 13 kV distribution class surge arrester modeled at the source-side of the voltage regulator terminals. The impact of the voltage shown in Fig. 3 on the surge arrester is quantified in Fig. 5, which shows the total accumulated energy duty for the surge arrester as a function of time. Fig. 5. indicates that within approximately 1.5 seconds the accumulated surge arrester energy would exceed its energy duty absorption capability.

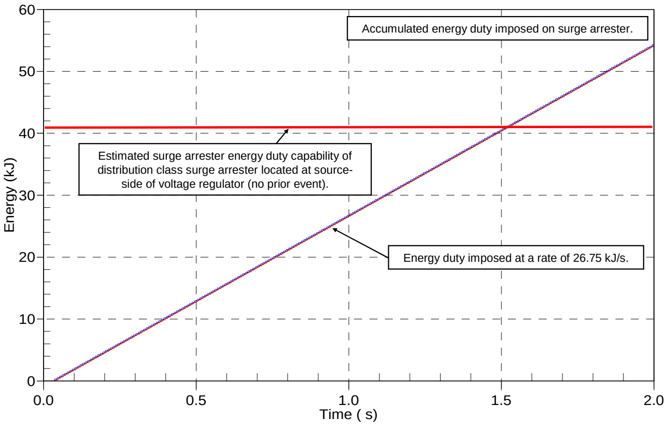

Fig. 5. Accumulated energy duty imposed on 13 kV distribution class surge arrester.

A 150 kVA wye-delta grounding transformer was then connected to the source-side terminals of the voltage regulator and the simulations repeated once again. Fig. 6 and Fig. 7 show the voltage across the regulator and saturated current through the regulator, respectively, with the grounding transformer connected. When the surge arrester was inserted back into service, negligible energy duty was imposed on it. With the grounding transformer connected to the circuit, the ferroresonance conditions were no longer present because the magnetizing current no longer had a series path with the cable capacitance in a radial, floating circuit.

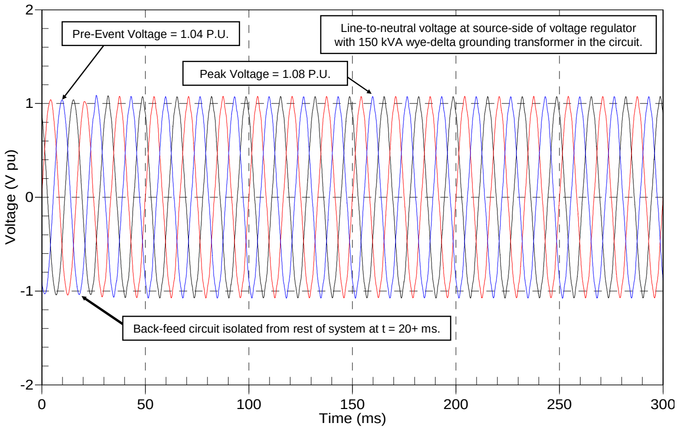

Fig. 6. Line-to-ground voltage at regulator under back-feed conditions with 150 kVA grounding transformer.

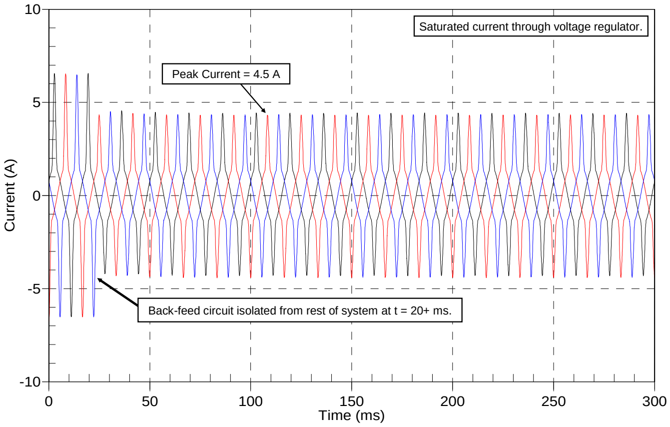

Fig. 7. Saturated current through regulator under back-feed conditions with 150 kVA grounding transformer.

V. RECOMMENDATIONS

The recommendations for the analysis were as follows:

- To mitigate potential ferroresonance conditions and excessive energy duty applied to existing surge arresters caused by the back-feed circuit, (1) one solution is to have the breaker that disconnects the 13 kV system from the source-side of the regulator located between the regulator and the capacitor bank and connect a wye-delta transformer line-to-ground in the regulator/cable 13 kV back-fed circuit. (2) Another potential solution is to insert a switching device on the load-side of the voltage regulator capable of detecting the back-feed conditions (such as through relaying) and opening within 0.5 s. Such a device would limit peak energy duty imposed on existing surge arresters to below their rated absorption capability.

- Breaker for solution (1) avoids ferroresonance caused by interaction of voltage regulator and capacitor bank, which is not mitigated by wye-delta grounding transformer.
- Wye-delta grounding transformer of solution (1) mitigates ferroresonance caused by interaction of magnetizing characteristics of voltage regulator and connected 13 kV cable circuit.
  - 50 kVA wye-delta transformer limits voltage to 1.20 P.U. and energy duty applied to rate of 0.038 kJ/s.
  - 150 kVA wye-delta transformer limits voltage to 1.08 P.U. and energy duty applied to rate of 0.037 kJ/s.

Solution (2) does not avoid ferroresonance conditions; rather it limits the duration of the event to where excessive energy duty would not be applied to existing surge arresters. Note that after opening of the switching device for solution (2), a trapped charge on the capacitor drains/oscillates through the saturation characteristics of the regulator, where the magnitude of the overvoltage is not a cause for concern.

VI. OVERALL SUMMARY OF FINDINGS

For radial distribution feeders fed by a voltage regulator, ferroresonance conditions can develop when the station breaker is open and a network protector at the low-side of a distribution transformer sticks closed. A sustained overvoltage dominated by the 3rd harmonic, i.e., zero sequence, occurs as the magnetizing current of the voltage regulator flows through the cable capacitance, based on the total Mvar charging of cable circuits. Ferroresonance can also occur when a voltage regulator is left connected to a distribution capacitor bank part of a radial back-fed circuit.

To avoid these conditions, a breaker can be placed between the distribution capacitor bank and voltage regulator, avoiding capacitor bank-regulator interaction; and a grounding transformer can be inserted in the regulator-cable back-fed circuit, eliminating the series path of the regulator with the cable capacitance for the regulator's magnetizing current to flow. Alternately, a switching device can be inserted on the load-side of the voltage regulator capable of detecting (such as through relaying) the back-feed conditions and open in sufficient time to limit the peak energy duty imposed on the surge arresters to within their rated energy duty absorption capabilities, for either the capacitor bank-regulator or cable-regulator ferroresonance conditions.

Based on the outcomes of the analysis, PSE&G is planning to install relay protection to sense the harmonic current that occurs under the back-feed conditions and trip the station-side switching device to eliminate the back-feed circuit.

VII. REFERENCES

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VIII. BIOGRAPHIES

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