An Automatic System for Frequency Regulation of a Power Plant Simulator

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***Abstract* - Power plant simulators offer an interesting environment for teaching and research of power electronics, automatic control, power generation, power systems stability etc. This paper deals with an automatic system for frequency regulation of a power plant simulator. It is based on a dc-dc converter controlling the speed of a dc motor that works as the prime mover of a three-phase synchronous generator. The system presents features such as "frequency droop with load increase", that allows paralleling of the generators and the possibility for adjusting the basic load set point of each generator. A current loop is also employed in parallel with the motor speed loop to assure safe start-up.**

I. Introduction

The power plant simulator available in the laboratory of our university, is composed of two sets of a dc motor and a synchronous generator, with voltage, current, power and frequency meters for operation monitoring as shown in Fig. 1. The speed of the dc motor and consequently the frequency of the generated ac power, can be varied in open loop via a rheostat connected to the field winding of the motor. Likewise, the magnitude of the generated voltage can be varied via another rheostat that controls the excitation current. The system has been used for many years in demonstrating basic power generation concepts, such as frequency and voltage variations of the output power due to changes in the active and reactive power demanded by the load from an unregulated system. Also, that generators must be synchronized, what is done varying their frequency and checking the voltage across a lighting sensor, before paralleling them.

A significant effort has been put forward towards improving the capabilities of this power plant simulator that would enable its use in more advanced studies. Pulse Width Modulated (PWM) power electronic converters have been added to the simulator, to allow automatic control of the generated voltage and frequency in the form of a Power System Stabilizer (PSS). Taking benefit of a transmission line model available in the laboratory, it is intended, as a medium term goal, to be able to compare the performance of Flexible AC Transmission Systems (FACTS) devices and a High Voltage DC (HVDC) link with PSSs in enhancing the stability and performance of a scaled-down power system.

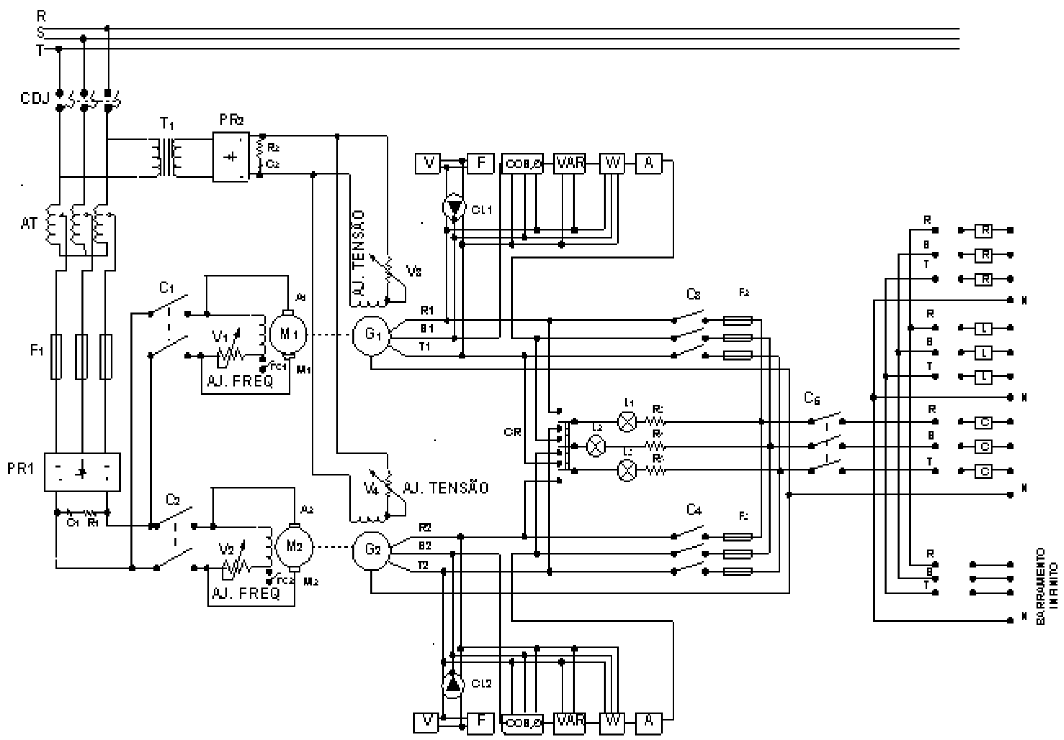

Fig.1 - Schematic diagram of the standard power plant simulator.

II. The Frequency Control System

This paper focuses on the frequency control system of a power plant simulator. Since a synchronous machine is used as generator in the simulator, the output frequency of the ac generated power can be regulated by measuring and controlling the speed of the dc motor. A schematic diagram of the power structure of the speed/frequency control system is shown in Fig. 2. It is fed via an autotransformer that steps the input voltage from 220 V (line-to-line) down to approximately 165 V, yielding a dc voltage of around 220 V at the output of a three-phase diode rectifier. This is the rated voltage for supplying the field and armature windings of a 373W dc motor. An IGBT-based PWM dc-dc converter controls the average value of the voltage applied to the armature of the dc motor (V_a) in order to regulate the rotor speed while the field winding current is kept constant. Fig. 2 also shows that a speed sensor, optical, connected to the rotor of the dc motor, and an armature current sensor based on a resistive shunt provide feedback signals for the control system.

The control circuit of the speed/frequency regulating system is shown in Fig. 3. It employs a standard carrier based PWM technique where the modulating signal (V_{mod}) is either the output of the Speed or the Current PI controllers. The current loop, that works mainly as a current limiter, was implemented because of the high (20 A) armature current demanded during start-up, even with no electrical load. It is worth mentioning that the rated steady-state current of the dc motor is 1.9 A. Paralleling of the two control loops was employed, rather than cascading, for allowing independent design and tuning of the PI controllers. An "OR" scheme, implemented with diodes at the input of the PWM comparator, favors the output of the PI controller with the lowest magnitude. Under normal operating conditions, it is the output of the Speed/frequency PI controller that prevails. However, during start-up, the current loop takes over, limiting the current that has to be switched by the IGBT, to a safe magnitude. This is a relatively brief operating condition, that ends when the rotor speed approaches the value set by the rotor speed voltage reference ($V_{\omega m\_ref}$). In such a case, the output of the speed/frequency PI controller falls below the output of the current PI controller and the first regains control of the PWM. The frequency droop characteristics of the speed/frequency loop are discussed in the following sub-section. An optically isolated IGBT driver, with negative voltage bias during the OFF time of the switch and short-circuit protection as described in [2] was used.

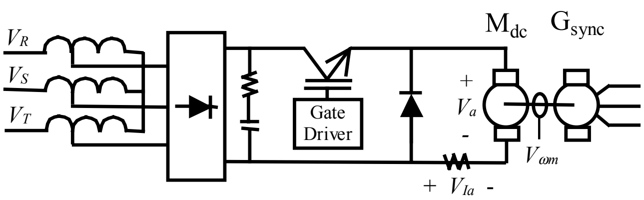

Fig. 2 – Power Structure of the speed/frequency regulator.

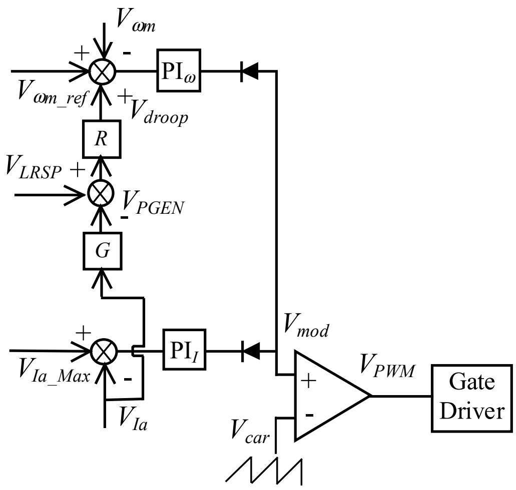

Fig. 3 – Control circuit of the speed/frequency regulator.

A. The Frequency Droop Characteristics

Isochronous, or constant frequency, controllers are interesting for isolated power generators. On the other hand, they can not be used when paralleling of generators is desired, since they would "fight" each other, each trying to pull the system's speed (frequency) to its own setting, that are usually slightly different. As a result, no stable operating point would be reached [3]. In such a case, a controller with a speed droop feedback loop should be used. It yields a small speed/frequency variation, as a function of the output power of the generator, typically 5% frequency deviation due to a 100 % load variation, but allows safe sharing of load variations [4].

For the power plant simulator under consideration, this characteristic has been implemented as shown in Fig. 3. The input of the speed/frequency PI controller is given by the speed voltage error ($V_{\omega m\_ref}$- $V_{\omega m}$) and an additional term whose magnitude is a function of the droop factor (R) and the difference between the *Load Reference Set Point* (V_{LRSP}) and the actual load supplied by the generator (V_{PGEN}). The latter is proportional, by a gain (G), to the dc motor armature current, which in turns is proportional to the machine's torque and to the active power supplied by the generator. This assumption is valid when the dc motor operates with constant field current and when the speed variation is relatively small, what is assured with a small droop factor R.

When the generated power is smaller than the *Load Reference Set Point* by ΔP, the steady state value for the rotor speed/frequency is given by

$$V_{\omega m} = V_{\omega m\_ref} + R\,\Delta P \tag{1}$$

The constant R determines the slope of the variation of the output speed/frequency from the rated value, set by $V_{\omega m\_ref}$, as a function of the output power deviation from the *Load Reference Set Point*, which can be varied via a potentiometer in V_{LRSP}. The value for the maximum armature current is set constant in V_{Ia_Max}.

III. Circuits of the Sensors and Control Loops

A. *Speed Sensor*

Rotational speed is usually measured with a dc tachometer, provided that it can be attached to the rotor. This was not the case with our power plant simulator. Alternatively, an optical *home-made* device, as described ahead, can be employed. The output signal of this sensor, whose electrical diagram is shown in Fig. 4, is a voltage waveform with a dc value proportional to the speed of the machine's rotor. A 16 teeth wheel attached to the rotor interrupts periodically a slotted infra-red opto-switch thus generating a train of pulses with 50 % duty-cycle. This voltage waveform is then passed through a monostable multivibrator and a RC low-pass filter. An operational amplified based voltage follower was employed to achieve low output impedance for the sensor.

There is an inherent voltage ripple on the voltage waveform at the output of the sensor, whose magnitude depends on the frequency and harmonic content of the train of pulses at the output of the multivibrator as well as on the corner frequency of the filter. A reduced harmonic content is obtained with a high duty cycle which allows the use of filters with higher cut-off frequencies and yields smaller delays. However, higher duty cycles can result in the saturation of the sensor for speeds above the rated. As a compromise solution, the pulse width of the monostable can be chosen to produce a 90 % duty cycle train of pulses with 480 (16*1800/60) Hz, when the rotor turns at its rated speed (1800 RPM). This way, the sensor can measure rotor speeds of up to 2000 RPM before saturating.

Fig. 5 shows the variation of the dc value of the output of the speed sensor as a function of the rotor speed. It should be mentioned that with the components presented in Fig. 4, a 0.5 $V_{P\text{-}P}$ ripple was found at rated speed.

B. *Current Sensor*

A simple 0.1 Ω / 5 W shunt resistor has been used for measuring the armature current of the dc motor. A feedback signal of the armature current is necessary for imposing a limit during start-up. Besides, as mentioned before, it is also needed for implementing the droop

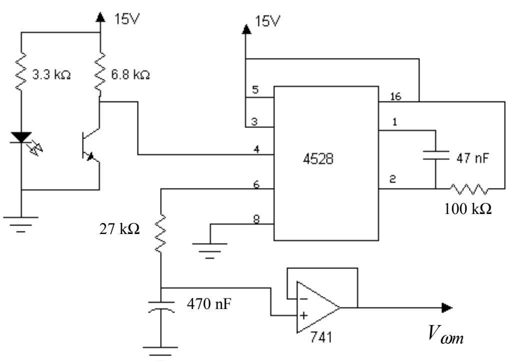

Fig. 4 – Rotor speed sensor circuit.

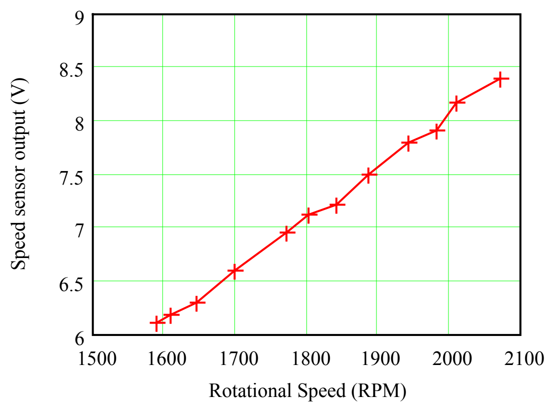

Fig. 5 – Variation of the speed sensor output as a function of the actual rotor speed.

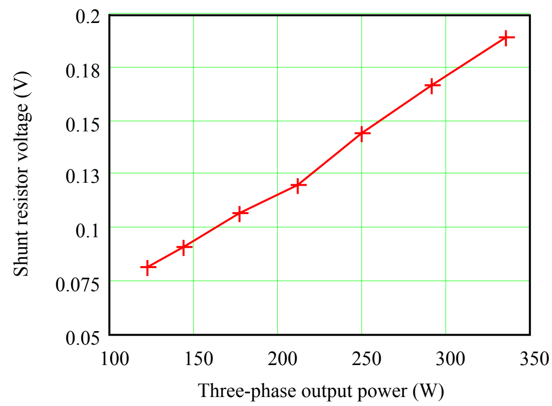

Fig. 6 – Variation of the armature current sensor output with the active power supplied by the generator.

characteristic, since the armature current of the dc motor is proportional to the active power supplied by the generator.

Fig. 6 shows the variation of the armature current of the dc motor with the output power of the synchronous generator for the system operating with constant (regulated) speed at rated value. The line-to-line rated voltage of the generator is 220 V and a 250 Ω resistive load is available in the simulator. To vary the output active power of the generator, its output voltage was varied by controlling the excitation current via a rheostat.

C. *Operational Amplifier Based Control Circuit*

The analog circuitry used in the frequency control system of the power plant simulator is shown in Fig. 7. The carrier sawtooth voltage waveform for the PWM is obtained as follows. A 555 timer generates a 10 kHz and 5 % duty cycle train of pulses that controls the charging, with constant current, and discharge of a capacitor (C_{ST}). The peak value of the carrier (10 V) is adjusted via potentiometer P_{VST}. The LM 311 compares with the carrier, the output voltage of either the Speed (OA_3) or the Current (OA_1) PI controllers, with the logic described in section II. Both PI controllers have their outputs limited between 0 and 10 V by a zener diode.

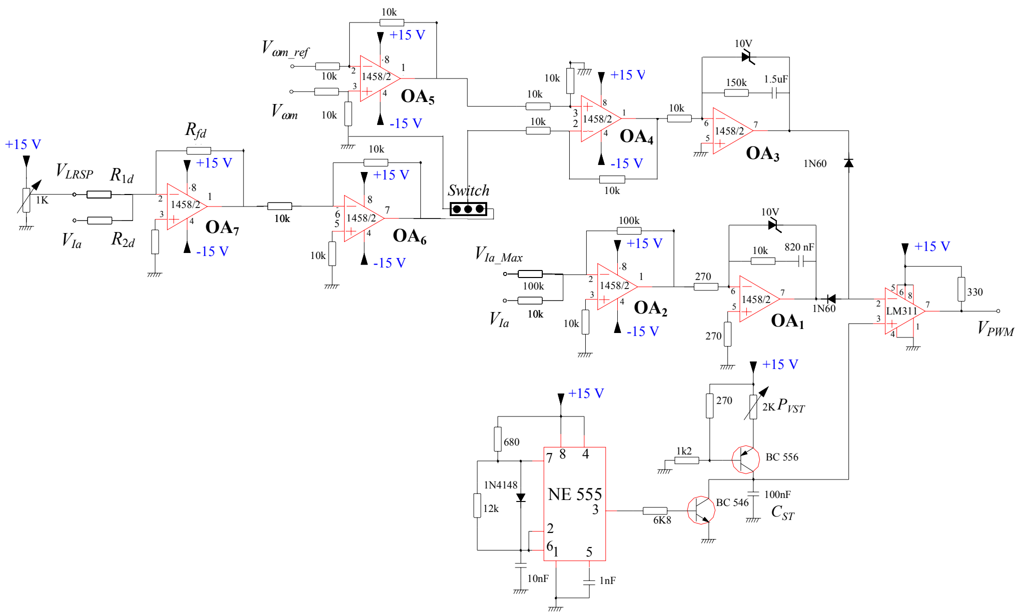

Fig. 7 - Analog control circuit for the frequency and start-up current of the power plant simulator.

Operational amplifiers OA_2 and OA_5 work as the Speed and Current error detectors. The subtractor block built with OA_4, was included into the circuit so that one can operate the system with constant frequency, when *Switch* is connected to the left side, or with droop, otherwise.

D. *Design of the Droop Block*

The signal that appears at the inverting input of OA_4 when the *Switch* is connected to the right, is the V_{droop} of Fig. 3. It can be shown that

$$V_{droop} = R_{fd}\left(\frac{V_{LRSP}}{R_{1d}} - \frac{V_{Ia}}{R_{2d}}\right) \tag{2}$$

because the polarity of V_{Ia} is taken as shown in Fig. 2.

When the generator is set to deliver rated frequency at rated load (335 W) and it does it, V_{droop} = 0.0 V. Then, one gets that

$$\frac{R_{1d}}{R_{2d}} = \frac{V_{LRSP\,(100\%)}}{V_{Ia\,(100\%)}} \tag{3}$$

It this study case, the magnitude of V_{droop}, when the generator supplies minimum load ($V_{Ia\,(0\%)}$ = 0.03 V) and the output frequency is above the rated by the droop factor (R = 0.05), is given by

$$V_{droop} = V_{\omega m\,(105\%)} - V_{\omega m\,(100\%)} \tag{4}$$

From Fig. 5 one sees that the speed sensor output is equal to 7.15 V at rated speed and 7.5 V at maximum speed (1890 RPM). Therefore V_{droop} = 0.35 V. Finally, R_{fd} can be calculated from the following relation

$$\frac{R_{fd}}{R_{2d}} = \frac{V_{droop}}{V_{Ia\,(100\%)} - V_{Ia\,(0\%)}} \tag{5}$$

Taking $V_{LRSP\,(100\%)}$ = 10 V and with $V_{Ia\,(100\%)}$ = 0.19 V, as shown in Fig. 6, the following resistors were chosen: R_{2d} = 3.3 kΩ, R_{1d} = 180 kΩ and R_{fd} = 6.8 kΩ

IV. EXPERIMENTAL RESULTS

Fig. 8 shows the waveforms of the dc motor armature current sensor and feedback signal of the rotor speed during start-up of the system with no electrical load. There one sees that the armature current is successfully limited around 4 A. In steady-state, with regulated speed, its magnitude drops to 0.3 A. Fig. 9 shows that the output of the current and speed PI controllers behave as expected. The first presents lower magnitude during start-up and then saturates positively while the second dominates the PWM operation, due to its lower magnitude, in steady-state. A significant amount of RFI is observed.

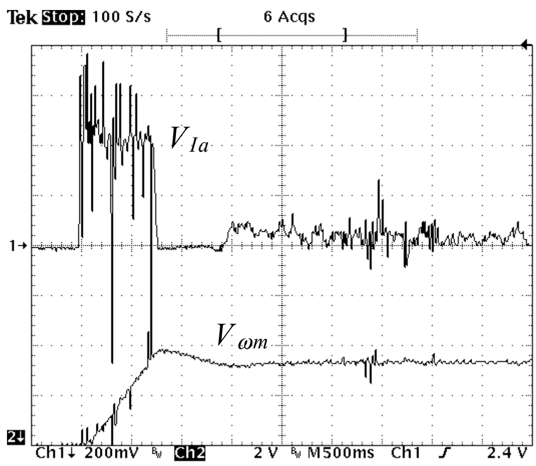

Fig. 8 – Output of the armature current and speed sensors during start-up.

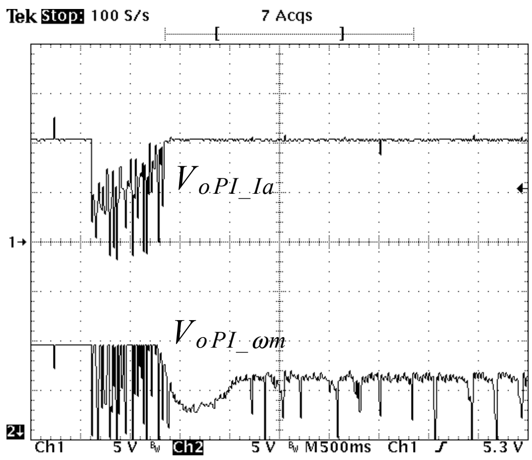

Fig. 9 – Output of the armature current and rotor speed PI controllers during start-up.

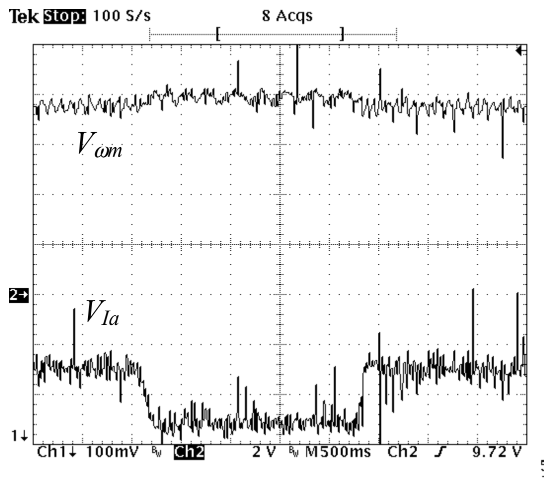

Fig. 10 – Output of the speed and dc motor armature current sensors for load variation when the system operates with frequency droop control.

Fig. 10 shows the variation of the output of the speed and dc motor armature current sensors when rated load is inserted and removed from the generator bus, by a contactor, and the system operates with frequency droop. There one sees that the rotor speed, and consequently the frequency of the output voltage, varies with the load as expected for operation with frequency to output power droop.

Table I shows the steady state value for the output of the rotor speed sensor when the load is varied and the *Load Reference Set Point* is adjusted for rated load. These values differ somewhat from the expected, due to different values, that were used for the droop block resistors, instead of those calculated as in section III.*D*.

On the other hand, when the *Switch* is connected to the left side, operation with constant speed (frequency) is obtained. This is verified, along with the output of the dc motor armature current sensor, in Fig. 11 for load variations from rated value to no-load. Although these results look good, the transient is atypically fast, compared to that of a real power generation unit, due to the small inertia of the power plant simulator system. Therefore, this system, as it is, would not be adequate for dynamic stability studies. As a possible solution, an extra metal disc with a large radius is sometimes coupled to the system's rotor. Alternatively, the speed loop PI controller could be designed to yield a smaller bandwidth, what would slow down the speed response of the regulation.

TABLE I
STEADY-STATE VALUES FOR THE SYSTEM SPEED OPERATING WITH DROOP

Load (%)	100	86.8	74.6	63.3	52.3	43.4	0.0
ωm (RPM)	1816	1832	1850	1858	1871	1880	1938
Δωm (%)	0.9	1.77	2.77	3.22	3.94	4.4	7.66

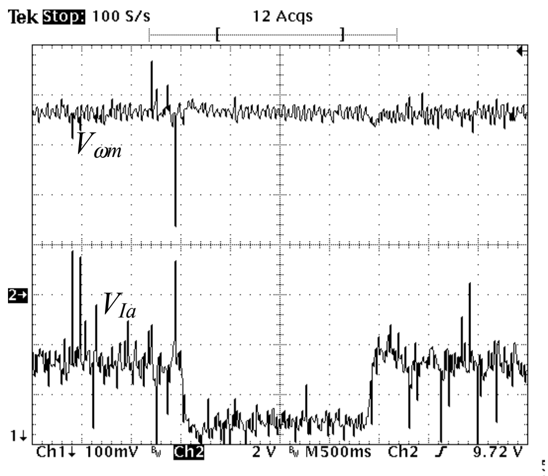

Fig. 11 – Output of the speed and dc motor armature current sensors for load variation when the system operates with constant frequency.

V. CONCLUSIONS

This paper has discussed an application of power electronics to allow automatic control of a power plant simulator used primarily for laboratory teaching classes. It was carried out as a final year project of undergraduate students with the support of graduate students. It was the first step towards the development of a small-scale system that can be used to analyze the application of FACTS controllers and Power System Stabilizers (PSSs) to enhance the performance of power systems.

VI. ACKNOWLEDGEMENT

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VII. REFERENCES

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