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ASPECTS ON CONTROL OF A VSC-HVDC TRANSMISSION LINK

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The VSC converter has attracted significant interest for high voltage and high power applications, due to its significant advantages. Nowadays, improvements in the power electronic field, such as the increase of the tolerable voltage, the capability of high currents and fast switching performances allow researchers to make efficient designs of voltage source converters that can be applied for many grid connected applications.

This paper investigates the means to control a VSC-HVDC link based on three-level NPC topology that interconnects two AC systems.

Keywords: HVDC Transmission, power converters, three-level NPC voltage source converter, VSC control system

1. Introduction

The need for transmitting power over long distances, along with the bigger and bigger demand for energy and the development of complex interconnected AC systems represent the main challenges for transmission technologies. Also, specific problems are expected with the renewable energies that should be integrated into the AC system that may be weak or may have insufficient reserve capacity in the neighboring systems.

In consonance with these challenges, power electronic technology is used to control load flow, reduce transmission losses and avoid congestion, loop flows and voltage problems. The recent advances in this field have led to innovative solutions with HVDC (High Voltage Direct Current) and FACTS (Flexible AC Transmission Systems) that can cope with these new challenges [1].

In some situations, it is economically and technically advantageous to introduce direct current links into the electrical supply system. DC transmission is the only feasible method of power transmission when two AC systems cannot be synchronized or when the distance by land or cable is too long for stable and/or economic AC transmission.

The first direct current commercial project was commissioned in 1954, consisting in a 10 MW undersea cable and linking Sweden and Gotland Island.

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Since then, the HVDC technology has been a natural choice for long distance transmission and asynchronous interconnection between systems.

Being the core of a DC transmission system, the converter can be based on thyristors or on insulated-gate bipolar transistors (IGBT). At the beginning, HVDC was based on Current Source Converter (CSC) or Line-Commutated Converter (LCC). Large amount of power could be processed, but, however full controllability of the system was not achieved and also high harmonic content was present. This converter was based on thyristors, semi-controllable power electronic devices. Once with the development of power electronics devices, the use of Voltage Source Converters (VSC) in high voltage applications became possible. They use IGBTs, which are fully-controllable devices, with both turn-on and turn-off functions [2].

Besides voltage and frequency control, VSC converters also allow the control of active and/or reactive powers. This control possibility represents an important advantage of the VSC converter against the traditional converter based on thyristors. In the near future, they will be increasingly more used in transmission and distribution systems. The VSC-HVDC concept was first used in 1997 by ABB, in a transmission link between Hellsjön and Grangesberg (Sweden), which was rated at 3 MW and ±10 kV.

The purpose of the paper is to see what are the components of a VSC-HVDC link interconnecting two different AC systems and how it can be controlled. This paper is structured as follows: the first part contains an introduction related to HVDC systems while in the second part it is presented the voltage source converter, with its benefits and its topologies. The model of the studied HVDC link is depicted in the third part, which also describes the control system for the three-level NPC VSC. In the fourth part of the paper there are presented results obtained from the simulation scheme and the last part contains final remarks on this analysis.

2. High Voltage Transmission Systems using Voltage Source Converters

The most straightforward VSC configuration that can be used to build up a three-phase forced commutated alternating voltage is the two-level Graetz bridge [3]. Each phase of the converter can be connected either to the positive DC terminal, or the negative DC terminal, producing a voltage output similar to a square-wave, highly non-sinusoidal.

Another topology for the VSC converter is the three-level VSC, that has less harmonic content than the two-level one and lower switching losses. The three-level VSC is most used in the neutral point clamp (NPC) and the cascaded flying capacitor structures. Voltage waveforms produced by both topologies will be the same, but still non-sinusoidal [4]. Fig. 1 shows the equivalent principle diagram of the three level NPC converter. Fig. 2 presents the equivalent circuit diagram of the three level NPC converter in *dq* coordinate system, and the mathematical model of this converter is depicted in (1) [5].

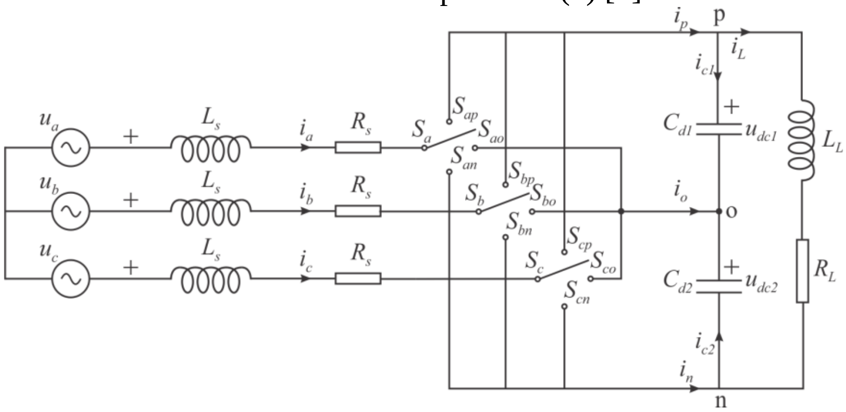

Fig. 1. Equivalent principle diagram of the three level NPC converter

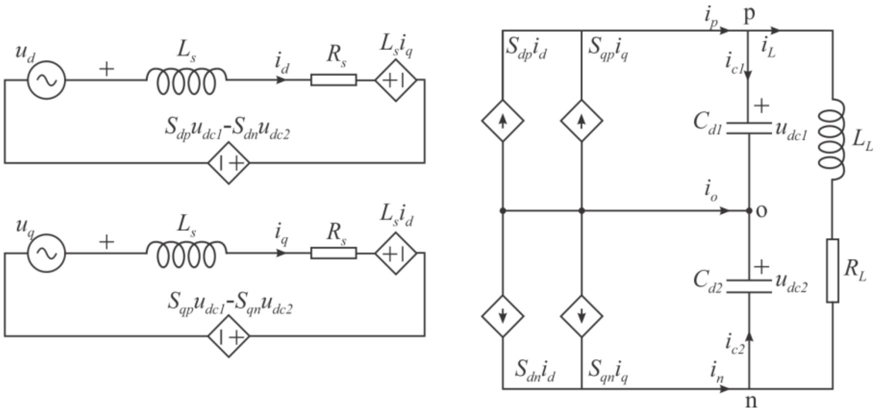

Fig. 2. Equivalent circuit diagram of the three level NPC converter in *dq* coordinate system

$$\begin{bmatrix} L_s\, di_d/dt \\ L_s\, di_q/dt \\ C_{d1}\, u_{dc1}/dt \\ C_{d2}\, u_{dc2}/dt \\ L_L\, di_L/dt \end{bmatrix} = \begin{bmatrix} -R_s & \omega L_s & -S_{dp} & S_{dn} & 0 \\ -\omega L_s & -R_s & -S_{qp} & S_{qn} & 0 \\ S_{dp} & S_{qp} & 0 & 0 & -1 \\ -S_{dn} & -S_{qn} & 0 & 0 & -1 \\ 0 & 0 & 1 & 1 & -R_L \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ u_{dc1} \\ u_{dc2} \\ i_L \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} u_d \\ u_q \end{bmatrix} \qquad \textbf{(1)}$$

where R_s and L_s are the equivalent resistor and AC inductor, C_{d1} and C_{d2} are the DC bus capacitors, R_L and L_L are the resistor and the inductor of DC load, u_{dc1} and u_{dc2} are DC capacitor voltages, u_d and u_q are equivalent voltages of three-phase grid voltage in *dq* coordinate, i_d and i_q are are equivalent currents of three-phase grid current in *dq* coordinate, i_L is load current and S_{dp}, S_{qp}, S_{dn} and S_{qn} are equivalent switching states in *dq* coordinate system [5].

Although the three-level NPC topology has advantages over the conventional two-level’s in high-power applications, it still has as drawbacks the voltage drifts and voltage ripples of the neutral-point in practical application [6]. The voltage drift phenomenon results in unsatisfactory operation or even failure of the inverter. In the same time the generated AC voltage will contain second or higher-order even harmonics. Thus, there is a need for equal voltage sharing among the DC capacitors, and the average of neutral-point voltage has to be maintained approximate to zero.

An important disadvantage of three-level NPC converter is the unequal distribution of losses among the switches. In order to overcome this drawback, a new multilevel converter was proposed in [6]: the N-Level Active Vienna neutral-point-clamped (NL-AVNPC), generalized for N odd voltage levels.

Thus, the basic three-level pole was extended to a multi-level one, whose development allowed the losses level to be considerably reduced and the voltage waveform generated by the VSC to be improved. Semiconductor development brought improved efficiency, compactness, better controls and cooling systems. Using a multilevel topology, the number of switch functions and power ratings can be increased. The differences between the configurations of VSCs are given by the comparison between the generated voltage waveform and the sinusoidal waveform, as seen from Fig. 3.

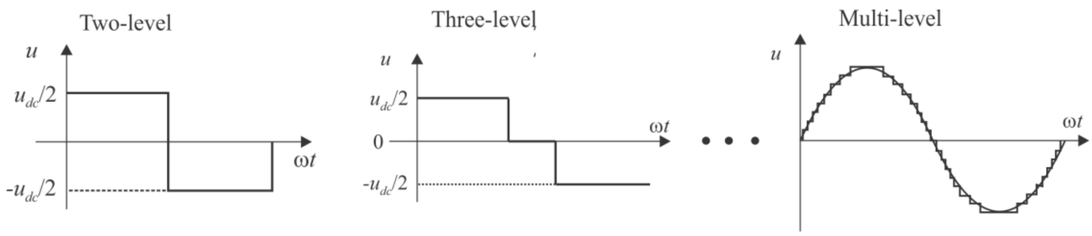

Fig. 3. VSC configurations: generated voltage waveforms

With advantages as the black-start capacity and no limitations regarding the distance, VSC technology can be used for certain applications involving supplying a load with no other source of generation or major urban areas through overhead transmission lines, underground or undersea cables. It can also be used to interconnect two or more AC power systems, synchronous or asynchronous, or as STATCOM devices in order to control voltage stability.The development of VSC-HVDC transmission systems has brought back the interest in multi-terminal DC networks for different applications, such as supergrids.

In a typical VSC-HVDC system, as presented in **Fig. 4**, two VSC are interconnected through a DC transmission line, that can be a cable or an overhead transmission line. The principal components of a VSC substation are: the DC side capacitor which provides a stable direct voltage, the phase reactor which facilitates the control of the active and reactive power exchange between the converter and the AC system, AC side filters necessary for high-order harmonic content of the generated AC voltage and the coupling transformer that allows the interconnection of the VSC converter with the AC system of different rated voltage.

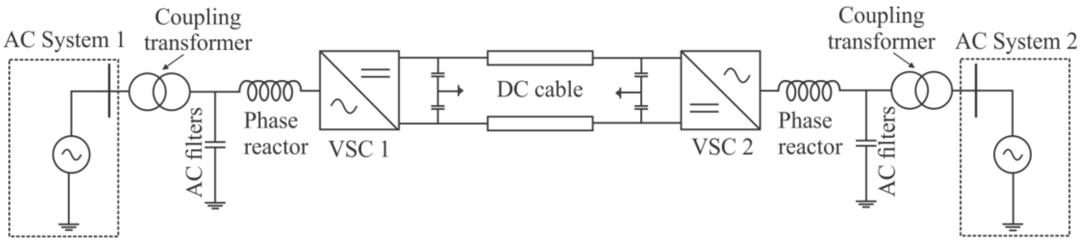

Fig. 4. Typical VSC-HVDC system

The control techniques used in grid connected converter systems may be classified as direct or indirect control strategies. The indirect control is characterized by a modulator which can be the Pulse Width Modulation (PWM) or other. It calculates the turn-on/turn-off times of converter's switches along a period through the evaluation of the voltage reference which is issued by the controller. On the other hand, direct control techniques determine a direct relation between the behavior of the controlled variable and the state of the converter's switches. The main advantage of indirect control techniques is the resulting constant switching frequency, whereas the direct control techniques offers faster transient responses.

In a VSC-HVDC link, one converter station has to control the direct voltage, and the other converter station controls the active power [8]. Thus, the active power is automatically balanced between the two converter stations.

3. Control scheme for VSC converter

The VSC control system uses mathematical transformations in order to obtain the components in different reference frames, like *abc* to *αβ* (2), *αβ* to *dq* (3) or the inverse transformation *αβ* to *abc* (4) [9].

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \frac{\sqrt{2}}{\sqrt{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} \cos(\omega t) & \sin(\omega t) \\ -\sin(\omega t) & \cos(\omega t) \end{bmatrix} \begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \frac{\sqrt{2}}{\sqrt{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} \tag{4}$$

The control system for the converter includes a fast inner current control loop and several slower outer control loops [3] and it is presented in Fig. 5.

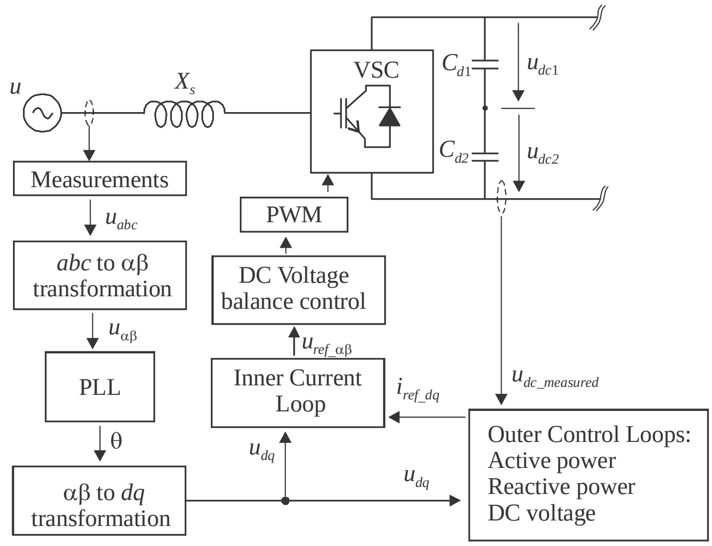

Fig. 5. Schematic control system for the voltage source converter

– The inner current loop tracks the current reference vector with the two components of the *dq* synchronous frame with a feedforward scheme to achieve a fast control of the current at load changes and disturbances. To reduce the error to zero in steady state, it is used a PI feedback of the converter current. The reference voltage limitation block limits the reference voltage vector amplitude. To generate the three-phase voltage references to the PWM, the control scheme uses the inverse *dq* and then, the inverse Clark transformation blocks.

– The phase-locked loop (PLL) is used to measure the frequency of the system and to provide the phase synchronous angle, θ for the *dq* transformation block in order to synchronize the delivered power.

– The outer loop regulators provide the reference value i_{ref_dq} for the inner current loop.

– The DC Voltage balance control loop objective is to minimize the voltage unbalance. It realizes this objective by the use of a DC mean voltage that represents the sum of the positive and negative pole voltages.

As stated before, the outer controllers are the ones responsible for providing the reference signals for the inner current loop. For this model, the outer loops are the active power, the reactive power and the DC voltage control loops and they are based on PI regulators. PI controllers performance is improved with the addition of feedforward paths with result in increasing the speed of response.

- The reactive power control block also contains an AC voltage control override block, with the purpose of overriding the reactive power regulator to maintain the AC voltage within a secure range in steady-state.
- The active power control block is designed in a similar way with the reactive power control block. It contains a DC voltage control override block, based on two PI regulators, that overrides the active power regulator to maintain the DC voltage within a secure range, during a perturbation in AC system 2 of the converter station controlling the DC voltage.
- The DC voltage control block uses a PI controller. The block is enabled when the active power control block is disabled. Its output is a reference value, for the I_d component of converter current vector and for the current reference limitation block. The latter is used to limit the current reference vector to a maximum acceptable value [10]. To transform the active and reactive power references, calculated by the active and reactive power controllers, to current references to the measured voltage at the filter bus it is used the current reference calculation block.

4. Case Study

For the interconnection of two 230 kV AC systems, it is used a HVDC link based on two forced-commutated Voltage Source Converters. The frequency of both AC systems is 50 Hz. The link is rated at ±100 kV, transmits 200 MVA and uses two cables with the length of 100 km. System's model is presented in **Fig. 6**.

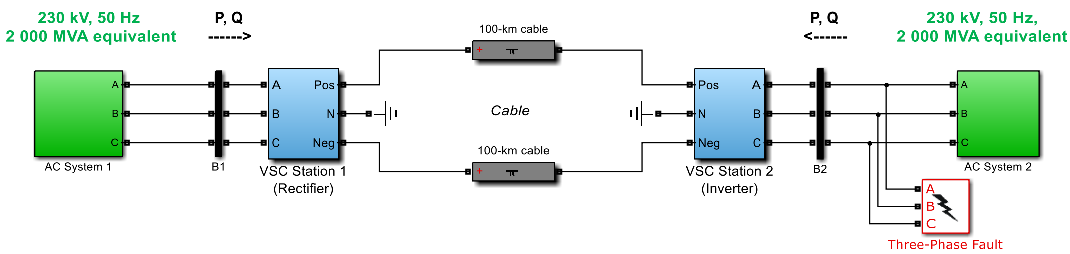

Fig. 6. Model of the VSC-HVDC link [10]

The two converter stations, the rectifier and the inverter, are three level NPC VSCs with carrier based pulse width modulation (PWM). The AC system blocks contain transformers and AC filters. The carrier wave has a frequency of

27 times fundamental frequency, i.e. 1350 Hz. Thus, the AC filters are tuned around 27th and 54th harmonics and are rated at 40 MVAr.

The two VSC stations contain the converter, DC filters, DC capacitors and a smoothing reactor. The high-frequency blocking DC filters are tuned for the 3rd harmonic. The rectifier and the inverter are interconnected through a 100 km cable and the three-phase fault is applied on the inverter AC side. This model was implemented in a Simulink program and uses SimPowerSystems™ blocks [10].

In the simulation scheme it is used a slow DC balance control. For carrier-based PWM modulation, the control scheme is based on output zero sequence voltage [7]. This control decreases to zero a positive DC voltage difference if the amplitude of the reference voltage which generates a positive midpoint current is increased at the same time as the amplitude of the reference voltage which generates a negative DC midpoint current is decreased. This is obtained by adding an offset component to the sinusoidal reference voltage. The waveform presented in Fig. 7 is the sum of the positive and negative pole voltages.

It can be observed an important drop of the waveform presented in Fig. 7 at 1.0 s. This is the moment when an important AC fault is applied in AC System 2. The sum of the positive and negative pole voltages is brought to zero shortly after the fault occurs.

In order to see if the control loops were correctly tuned, it is necessary to observe the dynamic response of the controllers to step changes applied to the active and reactive power and faults, as depicted from Fig. **8**.

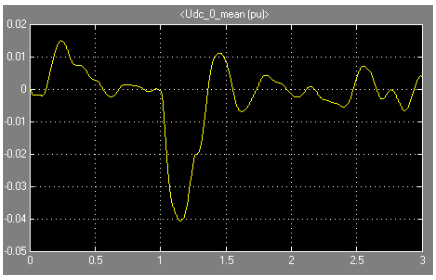

Fig. 7. DC voltage with balance control

(a)

(b)

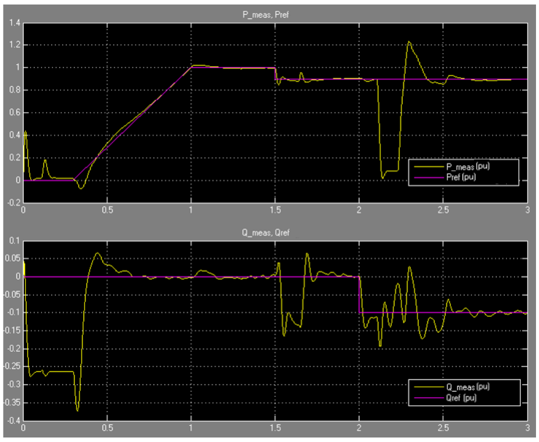

Fig. 8. Active power and reactive power step responses at connection point of AC System 1

Starting at 0.3 s, the active power is slowly ramped to 1 p.u. and steady state is reached in 1.2 s. A step change of -0.1 p.u. is then applied at 1.5 s. The resulting waveform together with its reference can be observed in *P_meas* subplot Fig. **8**a. As seen in the *Q_meas* subplot (Fig. **8**b), after a step of -0.1 p.u.

applied at 2 s, the reactive power is controlled to follow its reference value and it reaches it in approximately 1 s.

A three-phase voltage sag is applied through a three-phase programmable voltage source block at 1.5 s during 0.14 s at AC System 1, and the results can also be observed in Fig. **8**. It can be noticed that the reactive power is more affected by this fault. The steady-state is reached in 0.3 s for both active and reactive powers.

The ability to reject perturbations is confirmed with a three-phase fault applied this time in AC System 2, at 2.1 s, with a recovery of the system within 0.5 s. This can be noticed in the waveforms of DC voltage (Fig. 9a) and DC power (Fig. 9b). It can be observed from Fig. 9b that, when the fault occurs, the transmitted power on the line is almost zero and the DC voltage increases.

(a)
(b)
(c)

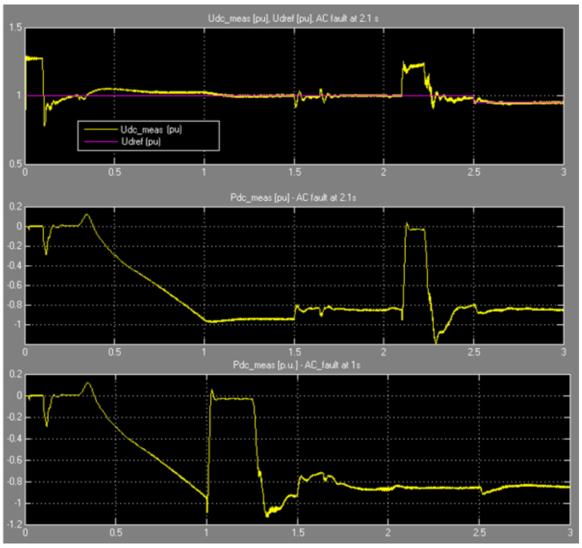

Fig. 9. DC parameters measured at the inverter side: (a) DC voltage;
(b) DC power when the AC three-phase fault is applied at 2.1 s;
(c) DC power when the AC three-phase fault is applied at 1.0 s

The DC voltage is limited in a fix range from the active power control loop in converter station 1 by a DC voltage control override that maintains the DC voltage within minimum and maximum limits.

If the AC fault form AC System 2 takes place at 1.0 s and lasts for 0.25 s, the DC power transfer is interrupted for the same period of time, but the system recovers well after less than 0.5 s, as can be seen from Fig. 9c.

4. Conclusions

This paper describes an adapted control scheme for the rectifier and inverter stations in a VSC-HVDC link interconnecting two AC systems, as proposed in [10]. For the two VSC converters, it is used the three-level NPC topology. The considered control loops are a fast inner current control loop and three slower outer control loops as the active power, the reactive power and the DC voltage control blocks. At the rectifier station there are controlled active and reactive powers, and at the inverter station there are maintained constant the continuous voltage and the reactive power.

The electric parameters waveforms (active and reactive power on the AC side and active power and voltage on the DC side) resulted from the presented control scheme and their changed forms in case of different perturbations as step changes or AC faults are presented in the end of the paper. An important factor to observe was the ability of the system to recover after their appearance.

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R E F E R E N C E S

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