MODELING MEAD-PHOENIX 500 KV PHASE SHIFTING TRANSFORMER IN EMTP STUDIES

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ABSTRACT

The 500 kV ac line from the Westwing substation near Phoenix to Mead substation in Nevada is 243 miles long and is planned for 70% series and 70% shunt compensation. The line also incorporates the first application of a 500 kV phase shifting transformer (PST) that enables 1300 MW transmission capacity through the line without inadvertent loop flows in the parallel interconnected system. This paper describes the EMTP models of the PST developed prior to the specification and the more elaborate EMTP (Electromagnetic Transients Program) models that were developed during the design stage.

INTRODUCTION

The Mead-Phoenix 500 kV project is part of the new 1300 MW transmission system between Arizona and California which is currently under construction and is scheduled for commissioning in December 1995. The Mead-Adelanto 500 kV ac project constitutes the other part of this transmission system. The integration of these two projects into the existing EHV transmission system between Arizona, Nevada and California is shown in Figure 1.

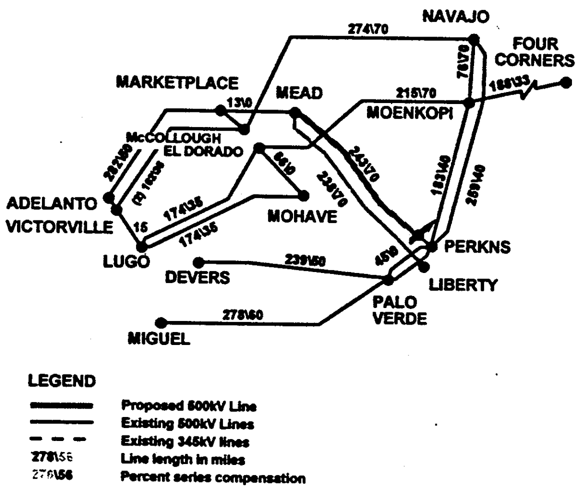


Figure 1. Mead-Phoenix 500 kV and other EHV Lines Between Arizona, Nevada and California

The 500 kV ac line from the Westwing substation near Phoenix to Mead substation in Nevada is 243 miles long and is planned for 70% series and 70% shunt compensation [1]. Two 500 kV, 650 MVA, $\pm$ 24 degrees (at no load) phase shifting transformers, operating in parallel will be installed at the Westwing substation. The PSTs provide variable phase angle shift between the input and output terminals of the PST. The on-load variable phase angle is provided by a tap changer in the secondary winding of the exciting transformer. Due to the size and phase angle requirements, the series and exciting units of the PST will be built into two separate tanks.

The PST is similar, but more complicated than the conventional EHV transformer, both in design and construction. Modeling the PST for transient studies is also complicated because of several windings involved and the mutual couplings between the windings. Internal resonance of EHV transformers has been of great concern due to the possibility that damaging overvoltages could occur, should the resonance be excited during operation. In view of the added complications of a phase shifting transformer, and this being the first application of a PST at 500 kV, studies were carried out prior to the specification and during the design stage, to identify the types of disturbances and switching operations that could affect the required insulation levels of the PST.

PRE-SPECIFICATION STUDIES

PST Design Features

A number of PST designs are available depending upon the type of control, such as discrete or continuous, and off-load or on-load, and the amount of phase angle to be controlled. Based on power flow studies, it was determined that a maximum phase shift angle of $\pm$ 16 degrees at full load, continuously variable on load will be required. Discussions with potential manufacturers interested in supplying the PST, and with transformer design experts, led to the following conclusions:

1. Considering the requirements of 16 degrees phase shift angle, 1300 MVA rating, and the manufacturers' shipping restrictions, it was concluded that two PSTs would be required each with 650 MVA rating, operating in parallel.

2. Consideration was given to the application of PSTs at 230 kV level, with 230 kV/525 kV step-up transformers, but the cost, increased phase angle requirement, and energy losses precluded that option.

3. Installation of a bank of single phase PSTs was determined to be not practical because of the complexity of the required external connections. It will also increase the risk of certain types of faults that would present difficult insulation and bracing design challenges.

Model for Pre-Specification Studies

The purpose of the pre-specification studies, which were conducted using EMTP, was two fold:
i) To determine the system operating conditions that could cause stress on the PST. If these stresses are of any significant, the PST supplier will be asked to study in more detail with the full detailed model of the PST.
ii) To identify the effects of PST on overvoltages at its terminals due to system disturbances.

The impedances, no-load phase angle, winding arrangements and other parameters of the PST are the assumed values based upon past experience. This model allows investigation of PST terminal voltages and not the voltages internal to the PST.

The PST model used for these studies consists of two separate transformers, an exciting transformer and a series transformer, which are interconnected as shown in Fig. 2. The primary or the high voltage winding of the exciting transformer is connected to mid point of the series winding of the series transformer. The secondary if the series transformer, also referred to as its exciting winding, is connected to the secondary of the exciting transformer. The amount and direction of phase shift angle is controlled by the tap changer in the secondary of the exciting transformer. The primary and secondary windings of the exciting transformer are connected in grounded star with taps on the secondary side. The series transformer is assumed to be provided with two primary windings that are connected series and two secondary windings connected in parallel. The secondaries of the series transformer are connected in delta configuration. The voltage and MVA ratings of each transformer and their assumed impedance values for a through put of 650 MVA at 25 degree phase shift (no-load) are also shown in Figure 2. The corresponding vector diagrams and the winding lay-out are shown in Figure 3. It should be noted that the winding lay-out is an assumed configuration for the purpose of pre-specification studies and the actual lay-out depends on specific design procedures and manufacturing practices.

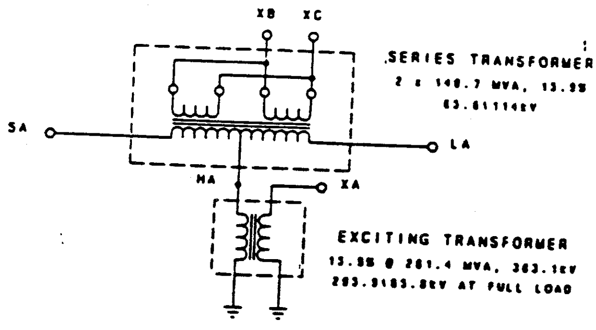


Figure 2. PST Model used for Pre-Specification Studies

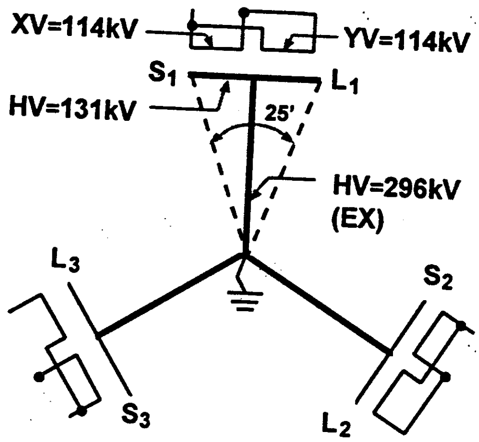


Figure 3. PST Vector Diagram for 650 MVA Rating

The EMTP does not yet have any built in models for representing the PST. Since there are several PST configurations and design differences in practice, the models also have to varied to meet the intended purpose of the model. For the purpose of the steady-state analysis, the individual units of a PST can be represented by the transformer models available in EMTP, and the interconnection between the units is performed externally.

The exciting transformer is represented in EMTP as a three-phase unit with 15.9% impedance. Parameters of the PST model used in EMTP are:

Exciting Transformer:
Three-phase unit, 281.4 MVA, 303.1 kV, 15.9 % Impedance;
Turns Ratio = 295.9 kV / 65.8 kV at full load.

Series Transformer:
Total rating of the two units 281.4 MVA
Each unit rated 140.7 MVA, with 15.9% impedance;
Turns ratio 65.6 kV / 114 kV

The nodes SA, SB and SC in Figure 2 are connected to the source side; LA, LB and LC are connected to the load side.

The PST connections were validated by determining the voltages and currents during open circuit and short circuit conditions. The voltage magnitudes and angles at various nodes with the load side open and the source side connected to positive sequence sources with the PST set at 100% tap position were evaluated. Similarly, the values were verified with negative, and zero sequence sources. The load side voltages were found to be 25 degrees advance with positive sequence source voltages, and 25 degrees retard with negative sequence source voltages, and no phase shift with zero sequence voltages applied at source. This indicates correct interconnection between the series and exciting transformers.

The voltages and currents with the load side short circuited and the source side connected to positive, negative and zero sequence source voltages were also calculated. From these, the through impedances were found to be 13.8% at 525 kV, 650 MVA for positive and negative sequences, and 6.9 % for the zero sequence, thus confirming the individual transformer impedances and their interconnection. It is also worth noting that there is no current flowing through the exciting transformer windings with zero-sequence source voltages applied. The variation of the PST positive sequence impedance as a function of tap position was also evaluated. The impedance varied from 6.9% at zero degree tap to 13.8% at 25 degree tap. This again confirms the accuracy of impedances of individual transformers and their interconnection. Representation of saturation was incorporated into the series and the exciting units through type 98 non-linear inductors.

The above described model is generally considered valid for frequencies up to about one kHz and is referred to in the paper as the low frequency model. It is known that EHV transformers, including PST, exhibit internal resonances in the frequency range 5 kHz to 100 kHz. To evaluate the effect of PST on transient overvoltages and at the terminals of the PST due to disturbances, the above described model was modified by adding capacitors at the 500 kV terminals to ground on each side of the PST. The capacitor size was varied to change the resonant frequencies.

The above described PST models were incorporated into the extensive Arizona-California 500 kV network model (Figure 1) and were used to study the following disturbances and the resulting transient overvoltages in the Mead-Phoenix 500 kV line:
i) PST switching: energizing, de-energizing, paralleling, de-paralleling, inserting and by-passing the PSTs.
ii) Transmission line faults: faults on the Mead-Phoenix line and on other lines and equipment in the vicinity of the PSTs.
iii) Series capacitor by-pass operation on the Mead-Phoenix line and other lines in the vicinity of the PSTs.

Cases were performed to determine the effect of the high frequency model as compared to the low-frequency model, and to determine whether the results would be affected if the PST model were resonant at the frequency corresponding to the distance to the line fault.

DESIGN MODELS

During the design stage, data became available to model the PST valid over a wide frequency range, with details about the nodes internal to the PST than that was possible for pre-specification studies. The number of the exciting transformer secondary windings and the disposition of the individual transformer impedances has differed from the values assumed during pre-specification studies. The secondary of the exciting transformer is arranged into four windings out of which three are coarse windings and the fourth is a fine winding that is equipped with taps. The manufacturer provided data for developing PST models in EMTP. The two models incorporated in EMTP are briefly described here.

Transformer Winding Model:

The representation followed here is similar to the pre-specification representation, however, the winding configurations and impedance values pertain to the actual design of the PST. The data provided enabled the PST representation through transformer models available in EMTP. The series transformer was modeled as conventional three-winding "saturable transformer" model with one exciting winding and two series windings. The five winding exciting transformer was represented through BCTRAN, an auxiliary routine available in EMTP [2]. BCTRAN routine calculates parameters for representing transformers as coupled impedances in the [R], $[L]^{-1}$ model. This model neglects capacitances between windings, from windings to the tank and core and between layers or windings. These capacitances and bushing capacitances were represented by adding a network of capacitances between winding terminal nodes, the data for which was provided by the manufacturer based on PST design parameters. The interconnection between transformers was performed externally. The magnetization characteristic was modeled by pseudo-nonlinear hysteretic reactor (Type 96). The resonance frequencies calculated from this agreed closely with those from the detailed model used by the manufacturer, however, damping at resonance frequencies was found to be less than the detailed model. This was attributed to the neglect of eddy current losses, which provide significant damping at high frequencies. The winding model includes only the fundamental frequency losses (load and no-load losses) and does not include the effect of eddy current losses that are dominant at high frequencies. The steady state performance of the model was validated by calculating no-load phase shift and short circuit impedance values at various taps as described earlier.

Linear Inductance Model

The PST was represented as a network with mutually coupled inductive branches and damping resistors to account for eddy current effects. The inductances are between winding branches and eddy current branches [3]. The winding resistances are represented across each branch and the eddy current resistances are represented separately as branches between the respective eddy current nodes and ground. The model has the following number of nodes and branches per phase:

Series Unit:
7 winding nodes + 7 eddy current nodes = 14 nodes per phase.
6 winding branches + 7 eddy current branches = 13 branches per phase.
Mutually coupled inductive branches per phase = 91
Number of resistive branches = 14
Total branches = 105 per phase.

Exciting Unit:
8 winding nodes + 4 eddy current nodes = 12 nodes per phase
5 winding branches + 4 eddy current branches = 9 branches per phase
Mutually coupled inductive branches per phase = 45
Number of resistive branches = 9
Total branches = 54 per phase.

The magnetization characteristic was modeled by pseudo-nonlinear hysteretic reactor (Type 96). The winding, inter-winding and bushing capacitances were also represented. The main advantage of this model over the transformer winding model is that this model represents more accurately the damping at resonance frequency.

Results with different models

Frequency response of the PST has been calculated for several terminal conditions. Results with transformer winding model and linear inductance model for two cases are shown:

Case 1: PST energized but not carrying load, tap 0
voltage applied at L1
L2 and L3 terminated with 300 ohms
S1, S2, S3 open

Voltage at source terminal for 1 pu voltage applied at L1 is shown for frequencies 100 Hz to 100 kHz (Figs 4a and 4b)

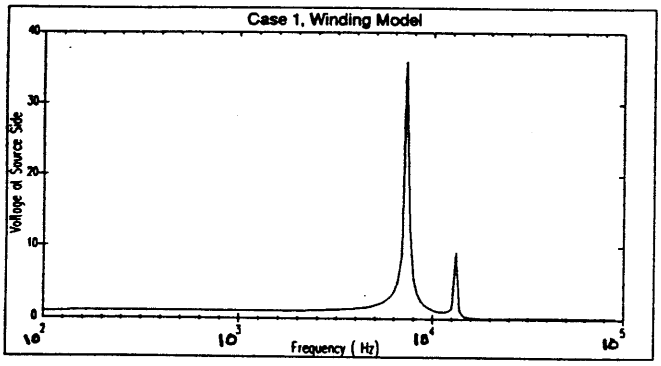
Case 2: PST bypassed, tap 0
Voltage applied at L1
L2 and L3 terminated with 300 ohms
L1, L2, L3 connected to S1, S2 and S3

Voltage at cross-over node (midpoint of the two series windings of the series transformer) is shown for 1 pu voltage applied at L1 (Figs 5a and 5b).

Results with linear inductance model show higher damping at resonance frequencies than with transformer winding model. Resonance frequencies and magnitudes for the two cases are given below and compared with the more detailed model used by the manufacturer.

Case 1
Winding Model: 35.9 pu, at 7.24 kHz
Linear Inductance Model: 10.7 pu, at 6.9 kHz
Manufacturer's Model: 10.0 pu, at 6.9 kHz

Case 2
Winding Model: 18.2 pu, at 11.0 kHz
Linear Inductance Model: 6.3 pu, at 11.0 kHz
Manufacturer's Model: 5.6 pu at 11.0 kHz



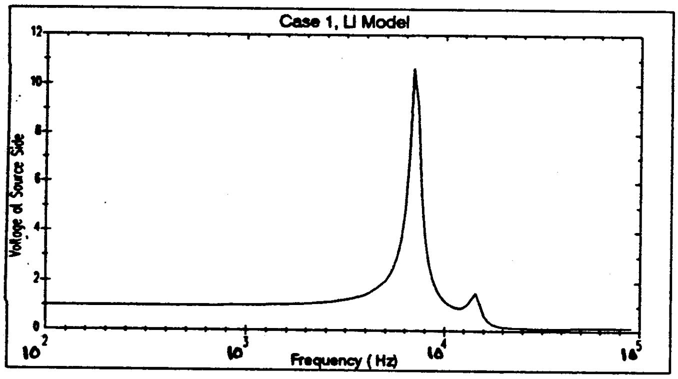
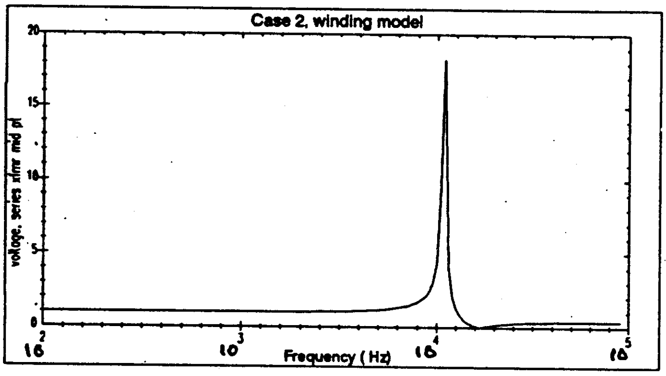
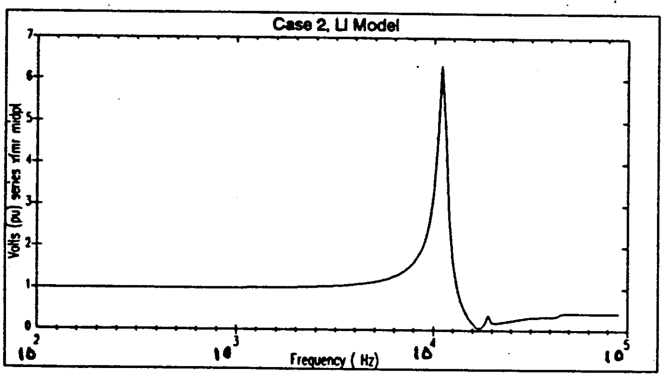


Fig 4 a and 4b. Results for Case 1 With Two Models





Figs. 5a and 5b. Results for Case 2, with Two models

CONCLUSIONS

Several EMTP models of the Mead-Phoenix 500 kV phase shifting transformer are described. Simplified models were used for pre-specification studies, which helped define critical cases to be studied in detail during the design stage. More detailed models with actual design parameters were developed in EMTP when the data became available, which are described in the paper. The PST is similar to an EHV transformer in several respects. However, it is also different in many aspects including differences in construction details. The internal resonant frequencies and amplification factors of both the PST and the EHV transformer depend, in general, upon several factors such as manufacturing techniques, design philosophy, number of windings etc., Resonant frequencies have to be ascertained for each and every unit separately. Resonant frequencies range from 10 kHz to 100 kHz. Damping at resonance frequencies have to be modeled accurately.

REFERENCES

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