Academic Model Development for Optical Voltage Transformer

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ABSTRACT

Optical Voltage Transformers (OVT) are designed to replace the conventional transformers. There are different optical voltage transformers developed by different suppliers. In this study, an academic model of optical voltage transformer is developed to compare with a real time optical voltage transformer (OVT) for steady state and transients response. The OVT impulse response is observed and saved the results to check that academic model of OVT can satisfactorily replace real time OVT or can be used as an OVT. An OVT's transfer function is developed by using the data of the response at frequency. Then a circuit with transfer function was designed. Developed circuit model is checked with the frequency response and is verified in the simulation. The outputs tell that the designed model of the circuit is an academic model of OVT.

Keywords: Optical voltage transformer (OVT), Steady state, Transient response, MATLAB, Transfer function.

1. INTRODUCTION

Optical voltage transformer (OVT's) are instrument transformer and they are used for measurements of high value of voltage and current at the grid. OVT's have two parts in them, which are opto and electronics, opto relates to the optical and electronic part which measure the value of voltage and current. Basically, In the beginning the sensors were used for measurements of voltage and current, but the measured values were not accurate values, then instrument transformers was introduced and they are of two type one is conventional current transformers and the other is conventional voltage transformers [1, 2]. Conventional current transformer was introduced and used for measuring but they also give faulty values because in Magnetic or Conventional transformer's the secondary side of the conventional

transformer's is magnetized and then the output signal is disturbed and cannot give the accurate value's. Same as Conventional Voltage transformers was introduced and used.

Then the Optical Potential transformers was introduced and used for measurements, they give the output accuracy slightly better than the magnetic transformers and then the Optical CT's are introduced which totally based on the optical principals and used for measurements and they were more accurate than the CCT's and CVT's. Then the Optical Voltage transformers are introduced and used for high values of AC and DC voltages [3, 4]. The Optical voltage transformer works on Pockle's effect and their performance depend upon on the material of the crystal which is used. Pockel's effect is the linear effect of electrical and optical device in which the electric field index is proportional to the refractive index. With development of crystal material, the performance of OVT's can be improved. The OVT's are used for high voltage transformer is more accurate as compared to the CVT's, they are smaller in size and lighter in weight [5-7].

Now the academic model of optical voltage transformer is developed by taking the response of real time OVT's with a fix amplitude and different values of frequency or with a varying input frequencies which shows that OVT's have a response same as low pass filter. By taking the frequency response data and converting it into transfer function through MATLAB and then through circuit modeling techniques a circuit is developed by using operational amplifiers. Then circuit simulation is performed in Proteous compared with the initial response of real time OVT's. By comparing, it is decided that OVT's model can replace or used on the place of real time OVT's. OVT's and Oct's are used for the measuring the values of voltages and currents so they are called Optical Instrument Transformers (OIT's). OIT's are less in weight and smaller in size then CIT's. So they can replace the CIT's.

Pockels effect is the basic principal of Optical Voltage transformers. Pockel's effect is the electrical and optical continues effect in which to the electric field index is proportional to refractive index. There are different types of crystals which was used for the OVT in the literature. Pockel's effect is nearly same as the Kerr effect; both discussed in detail [8]. In 1986, OVT was designed with the method name as the current sensing method by Cease, Driggans and Weikel [9]. Magneto-optic current transducer was also developed on the bases of current sensing method [10].

Voltage value's measurements are dependent on the sensors that are electric fields depended and MOCT was dependent only to magnetic fields, not to electric fields and MOCT was used for the measurements and there was only 0.8% deviation as compared to the magnetic voltage transformers. In 1995, a prototype of 132kV - 150 kV OVT was developed by the Pockel's effect, which was not include capacitor divider by Christensen [11]. A crystal of $Bi_4Ge_3O_{12}$ was used in the field created by two electrodes. The developed OVT was used for measurements, the voltage and temperature dependent conditions was tested and it works without any supply. Shape changes of electrodes effect the transformer ratio. Many publishers work on the AC measurements using the Pockels effect but there was so many faults in the DC measurements using the same method so they designed a new method for the measurements of DC values in the later studies. They presented the equipment tests. All the output results met with the values that was wanted and it verify that it can be used as the protection of DC power system.

Literature review reveals that in most articles, Optical voltage transformer have better response and now they are a very big part of applications of the power system, so for this reason they can replace the conventional voltage transformers. In the early research, presenters work on the improvement of the efficiency. For this purpose, OVT's have been used to show and compare with the conventional voltage transformer. The academic model of the OVT doesn't exit initially but the academic model of conventional voltage transformer was in existence. So we want to develop an academic model for the optical voltage transformers [12-16].

2. ACADEMIC MODEL OF OVT

A. Frequency Response Data

Basically, Frequency response data is that when the OVT is tested with a fix amplitude of input and a different or varying frequency, the response of the output was more likely as the Low-pass filter. The OVT was tested with fix amplitude of 1000 and a different frequencies varying from 60 to 16800, the output was decreasing from 1 towards zero and the phase difference was also changing. The frequency data is taken from [17].

B. Experimental setup

Basically the frequency response data is taken from an experiment which was the comparison between the OVT and Cvt as sown in Figure 1. The both transformers have different qualities. The first and the large difference of the OVT is it is light weight as compare to the Cvt. The test of the voltage transformers in the laboratory wants a very high voltage.



Figure 1: Experimental Setup for comparison of OVT and Cvt

A very high input of one hundred kilo volts, and a high voltage transformer of 5 kVA, and impulse generator of 200 kilo volts used for the comparison of the conventional and optical voltage transformers. They transformers were connected in parallel and then applied a very high input volt. The voltages were varied using a regulator. They supplied 80 kilo volts, which was high then the rated volts of the Cvt. They used a capacitive type voltage divider for the measurement of the applied voltages. For the value which they want at input of the voltages, capacitive voltage divider is used. The both are tested and the bandwidth of the output of the OVT was from 0.001 Hz to the 40 k Hz and the output of the Cvt was from 20 Hz to the 5 kHz. The OVT was given a variable frequency input. They measured the input

voltages and output voltages and compared them. The OVT's output is from 20 Hz to 5 k Hz, was tested with 14k Hz varying frequency from 50 Hz. The test setup is shown in the Figure 2.



Figure 2: Setup for frequency response of OVT

In this test setup a signal generator as a signal source is used of a one mega Hz frequency range. A power amplifier is used to amplify the frequency signal to 1000 W. A transformer of 1:60 ratio is used and supplied with the power amplifier which was in Nano mode. The input was with a fix voltages and a variable frequency from 50 Hz to 16 k Hz. They measured the output voltages with an oscilloscope of a very high range at the transformers secondary side. Two channels of the oscilloscope were used, one with the input signal measurements and the second with the output signal measurements. They compared both the inputs and the outputs and checked the frequency response for the different inputs in the 16 steps. The table.1 shown above is the proper frequency response data.

Table 1: Frequency response data of OVT

Frequency (HZ)	Amplitude	Phase (degree)
60	1	-0.86
300	0.992074	-7.78
1000	0.971343	-25.20
2000	0.924321	-52.42
4000	0.763616	-104.5
6000	0.601726	-149.4
7670	0.466982	-181.13
8200	0.435214	-197.05
10000	0.335722	-223.20
12000	0.242624	-259.78
14000	0.181136	-301.54
16800	0.137144	-353.95

3. DEVELOPMENT OF THE TRANSFER FUNCTION

Now, after the frequency data we have to get the transfer function from this data. We use the frequency response data and convert this data into the transfer function in the MATLAB. We use "invfreqs" command which converts the nominator and denominator using phase difference and frequency provides the transfer function. We use frequency data and bode converts all the values for the invfreqs command which converts into (b, a) the tf command uses for the transfer function. Here is the transfer function of the given data and also for the circuit of our academic model of OVT.

H(s)

$$=\frac{-3.26\times10^9 s^3 + 4.833\times10^{14} s^2 - 6.171\times10^{19} s + 3.54\times10^{24}}{s^5 + 2.501\times10^5 s^4 + 4.54\times10^{10} s^3 + 4.45\times10^{15} s^2 + 2.095\times10^{20} s + 3.566\times10^{24}}$$
(*i*)

Here is the phase and magnitude diagram of the given data in figure 4. Bode plot shows the magnitude of the data converted in the db and same as the phase of data shown in the degrees.



Figure 3: Bode plot of the frequency response data

A. POLES AND ZEROS

Now we are going to convert this transfer function into the equivalent circuit model of the OVT. First of all the transfer function is converted into the poles and zeros using the MATLAB again with the command of [r,p,k]. Then the transfer function is converted into the poles and zeros.

$$H(s) = \frac{-3.26 \times 10^9 s^3 + 4.833 \times 10^{14} s^2 - 6.171 \times 10^{19} s + 3.54 \times 10^{24}}{s^5 + 2.501 \times 10^5 s^4 + 4.54 \times 10^{10} s^3 + 4.45 \times 10^{15} s^2 + 2.095 \times 10^{20} s + 3.56}$$

 $s^5 + 2.501 \times 10^5 s^4 + 4.54 \times 10^{10} s^3 + 4.45 \times 10^{15} s^2 + 2.095 \times 10^{20} s + 3.566 \times 10^{24}$ After the poles and zeros command the transfer function is converted into the poles and zeros. Then we convert it into the partial fractions using the poles and zeros equation. Using the same code in MATLAB and again for poles and zeros and here are the poles and zeros of this data.

Zeros	Poles
(-0.1261 - j0.1297)×10^5	(-0.4610 + j1.4201)×10^5
(-0.1261 + j0.1297)×10^5	(-0.4610 - j1.4201)×10^5
(-1.2140 +j2.3843)×10^5	(-0.6015 + j0.2686)×10^5
(-1.2140 -j2.3843)×10^5	(−0.6015 - j0.2686)×10^5
2.6802×10^5	-0.3724×10^5

Table.2: Zeros and Poles of the Real Time Data

4. DEVELOPMENT OF EQUIVALENT CIRCUIT MODEL

There are different steps for the circuit model. Firstly, we convert the poles and zeros in the form of partial fractions using the general equation given below.

4.1.1 Partial fraction:

Now using this equation same as all the poles and zeros converted in to the partial fraction.

• $H_1(s)$ -	$H_1(s) = \frac{(2.6802).10^{5}}{(iv)}$	
	$s - (-0.3724).10^{5}$	
•	H. (c) = $\frac{(-0.1261 - j0.1297).10^{5}}{(v)}$	
$11_2(8) =$	$s_{-(-0.4610+j1.4201).10^{5}}$ (V)	
• H ₃ (s)=	$H_{s}(s) = \frac{(-0.1261 + j0.1297).10^{5}}{(vi)}$	`
	$\frac{113(5)}{s-(-0.4610-j1.4201).10^{5}}$,
•	$\mathbf{H}(s) = \frac{(-1.2140 + j2.3843).10^{5}}{(vii)}$	5
$11_4(8) -$	$s = (-0.6015 - j0.2686).10^{5}$	IJ
	$H_{-}(s) = \frac{(-1.2140 - j2.3843).10^{5}}{(vii)}$	5
- 115(8)-	$\frac{115(5)}{s-(-0.6015+j0.2686).10^{5}}$	ц)

Here is the poles and zeros map of the transfer function.



Figure 4: Poles and Zeros map

3.4.2 CONVERSION INTO THE CIRCUIT:

Now the next step is to convert the partial fractions into the circuit. We learned from a circuit design book that a partial fraction transfer function is converted into the circuit using the operational amplifiers.

Now here are the general forms of the transfer function and their equivalent circuits. If we have the same transfer function, we can use the circuit in the replacement.

We have two cases here.

Case1:

If the transfer function is in this form,

 $H(s) = \frac{k}{s - (p)}....(ix)$

If we have the general form of the transfer function like the given, then we use the circuit which is given here.



Figure 5: Circuit for the Eq. (ix)

Case2:

Now if we have the transfer function like this general form then we are going to use the circuit given below.

$$H(s) = \frac{-k(s+z)}{[s-(\alpha-j\beta)][s-(\alpha+j\beta)]}\dots\dots(x)$$

If we have the transfer function same like this, then we convert the transfer function into two different circuits using together.

The transfer function is divided into two parts one is H' (s) and the other is H" (s)

Like numerator and denominator both have different circuit. H'(s) = -k(s + z).....(xi)

Then the circuit is going to use is given below.



Figure 6: Circuit for the Eq. (xi)

If we have the circuit same like this general transfer function, then we use the circuit given below.

$$H''(s) = \frac{1}{[s - (\alpha - j\beta)][s - (\alpha + j\beta)]} \dots \dots (xii)$$

In this case the R_1 is equal to the w_o and the capacitor in the above circuit is equal to the k and the resistance is equal to the 1/kz.



Figure 7: Circuit for the Eq. (xii)

3.4.3 CIRCUIT MODEL:

Now for the circuit model we calculated the values of each circuit and then the proper conversion of the partial fraction transfer function into the complete circuit.

$$H(S) = \frac{-3.2688 \times 10^9 S^3 + 4.6833 \times 10^{14} S^2 - 6.171 \times 10^{19} S + 3.54 \times 10^{24}}{S^5 + 2.501 \times 10^5 S^4 + 4.54 \times 10^{10} S^3 + 4.453 \times 10^{15} S^2 + 2.095 \times 10^{20} S + 3.566 \times 10^{24}} \dots (xiii)$$

Now we are going to convert the partial fraction transfer functions into the circuits by comparing with the general forms.

$$H(s) = \frac{(2.6802).10^{5}}{s - (-0.3724).10^{5}} + \frac{(-0.1261 - j0.1297).10^{5}}{s - (-0.4610 + j1.4201).10^{5}} + \frac{(-0.1261 + j0.1297).10^{5}}{s - (-0.4610 - j1.4201).10^{5}} + \frac{(-1.2140 - j2.3843).10^{5}}{s - (-0.6015 - j0.2686).10^{5}} + \dots (xiv)$$

Circuit #1

$$H_{l}(s) = \frac{(2.6802).10^{5}}{s - (-0.3724).10^{5}} \dots (xvi)$$

Now the values with the calculations comes here for resistance 'R' and the capacitor 'C'.

R=-K/p

R=7.34 Ohm

C=1/k

C=3.64uF

Now using the values the circuit becomes.



Figure 8: Circuit for first partial fraction transfer function

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Circuit # 2

Now for the next two pairs we are going to represent them in the form of two transfer function which basically add up and make a combined circuit.

$$H_{2}(s) = \frac{(-0.1261 - j0.1297) \cdot 10^{5}}{s - (-0.4610 + j1.4201) \cdot 10^{5}} \dots (xvii)$$

$$H_{3}(s) = \frac{(-0.1261 + j0.1297) \cdot 10^{5}}{s - (-0.4610 - j1.4201) \cdot 10^{5}} \dots (xviii)$$

Now taking the LCM of the both these transfer functions and then after this LCM the final form comes:

$$H_{23}(s) = \frac{-0.2522 \times 10^{5} (s + 0.999 \times 10^{5})}{[s - (-0.4065 + j1.4201).10^{5}][s - (-0.4610 + j1.4201).10^{5}]} \dots (xix)$$

Which is the same as the case2 so we use the nominator as the H_{23} '(s) and the denominator is represented as the H_{23} "(s).

Now here is the calculations for the circuit.

$$w_{o} = \sqrt{\alpha^{2} + \beta^{2}}$$

R₁ = 0.5475 ohm



Figure 9: Circuit for the second and third partial fraction transfer functions

Circuit #3

Now the same as for the next two pairs of the transfer function we convert it into the general form equation taking the LCM and then we find circuit values and convert it into the relative circuit form.

$$H_4(s) = \frac{(-1.2140 + j2.3843).10^{5}}{s - (-0.6015 - j0.2686).10^{5}}....(xx)$$

$$H_5(s) = \frac{(-1.2140 - j2.3843).10^{5}}{s - (-0.6015 + j0.2686).10^{5}}....(xxi)$$

Now we take the LCM and convert it into the two forms and then change them into their relative circuit and use them to perform work.

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 $H_{45}'(s) = -2.428 \times 10^5 (s - 1.13 \times 10^5) \dots (xxiii)$



Figure 10: Circuit for the second partial fraction transfer function

The designed circuit added into the proteous and to perform the simulation. We use a adder circuit to add all the output of the three circuits. Here is the final circuit of all the partial transfer fractions.



Figure 11: Circuit for simulation

5. RESULTS AND DISCUSSIONS

Simulation is the process in which the whole circuit is performed using the software and the values are checked in the proteous. We performed this simulation in proteous and checked for the different values of the frequencies. We use the one volt input and the take the outputs with respect to the different values of the frequencies.



Figure 12: Circuit for Simulation in Proteous

We performed this circuit in proteous and check the values for different inputs. Firstly, when there is the input is F=50 Hz then there is the output 1 v which is the required out with the 1k input. Then when changing input F=400 Hz then the output comes 0.95 v. Then by changing the values of frequency and we get the outputs.



Figure 13: Simulation results on 50 Hz

Frequency (Hz)	Output (v)
50	1
400	0.95
1000	0.86
1500	0.8
2000	0.75
4000	0.66
6700	0.6
8600	0.55
10200	0.45
13000	0.36
14000	0.21
16000	0.11



Figure 14: Simulation Graph4

Simulation Graph shows the decrease in the values from the changing input frequency from low to high. As the frequency increases it decreases the value of the output voltage. We can see when the frequency comes closer to the 16k then the value becomes very small which shows that its response is the same as the response of the real time data of the optical voltage transformer.

6. LABORATORY SETUP

We used the operational amplifiers, resistors and capacitors to make the circuit of the academic model of the optical voltage transformers. We made different inputs to the circuit and check the results at the output. Basically OVT responses as a low pass filter in the real time so we give input frequency 50 Hz and there was output near 1v. Same as we check for the different values of the varying frequency and saved the results.

Table.4:	Hardware Results
Frequency (Hz)	Output(v)
50	1
420	0.98
1400	0.89
2000	0.8
4000	0.7
5860	0.6
7670	0.55
8300	0.5
10100	0.4
12000	0.3
14000	0.2
16000	0.1



Figure 15: Experimental form of the OVT

Hard form result graph shows the working of the project with the input increasing of the input from 50 Hz to the 16k. As we can see the initial value is of the input is 50 Hz and the output is 1v and then with the increase in the frequency the value of output decreases.



Hardform Result Graph

Figure 16: Hard form Results graph

RESULTS AND COMPARISON:

We plotted the graph between the Simulation and the hard form results. In the graph Mag-S represents the simulation results and the Mag-H represents the hard form results. With the changing frequencies graph goes down towards low values and there is a very small difference between the simulation and the hard form result which conclude that the developed model is going to use as the academic model of the optical voltage transformer. There is a small difference between the two frequencies near 2000 and then near the 10k frequencies.



Figure 17: Comparison Graph between the Simulation and the hard form

This graph presents the final comparison of the hard form results and the simulation results which are very close to the real time data of the optical voltage.

7. CONCLUSION

We developed the academic model of the optical voltage transformer using the frequency response data and then convert that data into the transfer function using the MATLAB command "invfreq" to get the nominator and denominators. Then "tf" command converts them into the transfer function. Then the transfer function is converted into the partial fraction to convert or design the circuits. The partial fraction transfer function then converted into the circuit and a full circuit was designed. Then the simulation is performed in the proteous and the hard form is presented with the values or response with the varying frequency. We concluded that the designed circuit model can be used as the academic model of optical voltage transformer. In future we want to make this project for high values, like for the range of high and changing values of the input.

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