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The impact of using phase-shift transformers on transmission lines

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ABSTRACT

Phase shift transformers (PST) are a special type of transformers used to regulate active and reactive power on 3-phase transmission networks by adjusting the difference of voltage phase angle between system nodes. Problems related to power flow and stability, particularly voltage stability issues, are important at the extra high voltage (EHV) and ultra high voltage (UHV) levels due to their extreme sensitivity to active and reactive power changes. Several studies investigated these problems using three-phase systems. Accordingly, this research aims to demonstrate the impact of using PST with single and double transmission lines and to compare its performance under various operational modes.

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1. INTRODUCTION

Phase shifting transformers (PST) are a special type of transformers used to control the active and reactive power flow on 3-phase transmission lines. PSTs are critical for electrical power interconnection between the three neighbouring countries: Jordan, Egypt, and Iraq [1]-[6]. The control in PSTs can be accomplished by adjusting the voltage phase angle difference between the system nodes as illustrated in Figure 1 [6]-[9].

The key operating principle of the PSTs is to inject a phase-shifted voltage source into the line through series-connected transformers. A shunt transformer can be used to feed PSTs. The configuration of these two series and PST transformers are primarily responsible for the phase shift [10]-[13].

Two major configurations are of particular interest: the power flow between transmission systems operating in parallel, one of which includes a PST; while the other does not include a PST [14]-[17]. The nominal primary voltages of each winding: 0-120-220 V are suitable for delta connection at 120 or 220 V, and the nominal secondary voltages of each winding: 0-120-220 V are suitable for delta connection at 120 or 220 V [18]. The transmission line shown in Figure 2 is connected to a 220 V input line voltage, with a socket of 30 V as a winding phase shifter [19].

If the power flow is not balanced, an optimum power grid will not be obtained, resulting in underutilization and line overloads [20]. The use of PSTs allows setting voltages at interconnection nodes and hence, power flow can vary. Accordingly, the use of PSTs makes it possible to adjust the transmitted active power of the line by varying the voltage step at the start [21].

During the current study, a simulator of energy transmission line type SLE/2 with single and double transmission lines in power lap was used to investigate the impact of using PST [22]. The length parameters for the used transmission lines are shown in Tables 1 and 2. The SLE/2 will be fitted with a power supply with two output line voltages (120 and 220 V), that are proportional to the feeding voltage [23]-[25]. To calculate the voltage variance, the diagram shown in Figure 3 was used.

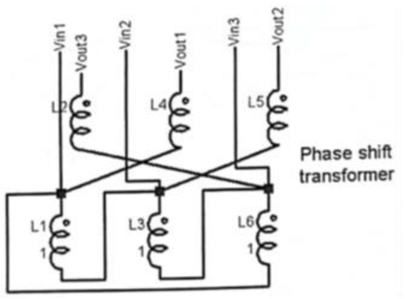

Figure 1. Phase shifting transformer

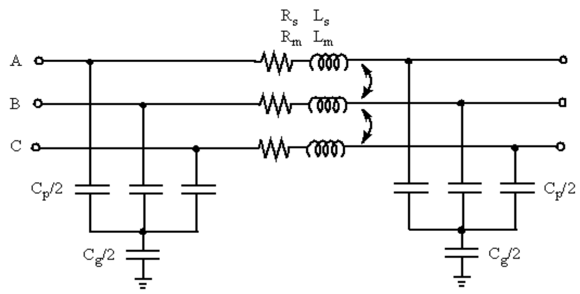

Figure 2. Transmission line

Table 1. Length parameters for the employed transmission line

L/km	Xl/km	R/km	C/km
1.2 mH/km	0.376 Ohm/km	0.229 Ohm/km	9.43 nF/km

Table 2. Parameters of the experiment

Parameter	Value
XL	26.7 ohm
Frequency	50 Hz
R1, R2, R3	16 ohm
Feed voltage	150 V
Input power	120 or 220 KV
Transmission line length	70 Km
Load power	160 MVA

Phase parameters for each line are shown:
L_1=L_2=L_3=85 mH;
R_1=R_2=R_3=16 Ohm;
C_1=C_2=C_3=C_4=C_5=C_6=0.33µF
X_1=26.7 Ohm at H=50 Hz.

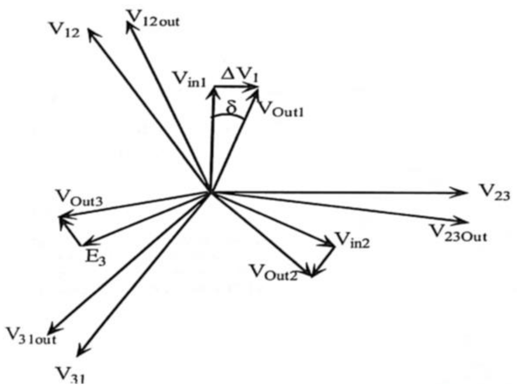

Figure 3. The voltage variation referred to the diagram

$$\Delta V\% = 100\,(V1 - V2)/V2 = (100\sqrt{3}\, I(R\, cos\emptyset 2\; X\, sin\emptyset 2))/V2 \quad (1)$$

The line efficiency will be calculated using as (2):

$$\eta = (1 - [(P1 - P2)/P2]\ ) * 100 \qquad (2)$$

where P1 - is power at the starting point, and P2 - is power at the arrival.

2. EXPERIMENT SCENARIOS AND SIMULATION OF PST MODEL

The simulations for the current study were done using MATLAB. These models are suitable for studying the effect of using phase-shift transformers on transmission lines to transport power energy. Table 3 shows the elements used in the simulation models for Figures 4 and 5, and the difference between these two models is that number 4 is for a single transmission line and the second is for a double transmission line. These models are built to compare their results with those obtained by the experimental method by using a simulator of the energy transmission line type SLE/2. Section 3 results and discussion contains a list of the comparing results.

Table 3. Show the elements of simulation models

Name of element	Function
RMS	Give the parameter's root main square value
Display	Display the value measurement
Scope	Show the curve of the parameter
Power	provides both active and reactive power in an instant
Dot	Dot current & voltage to measure apparent power
Sum	To have apparent power on the line
Three-phase series RLC branch	To determine the transmission line parameter
Three-phase source	providing three-phase power
Three-phase V-I measurement	To measure three-phase instantaneous voltages and currents in a circuit
Voltage measurement	To determine the voltage between terminals' value
Current measurement	To determine the amount of current flowing through a conductor
R-load	Consume power from the source
Ground	To protect devices in the system

Several scenarios were employed to collect data and evaluate the simulation results, as follows:

A. A single transmission line according to the following scenario:
- No-Load line without phasing
- Load line without phasing
- No-Load line with phasing
- Load line with phasing

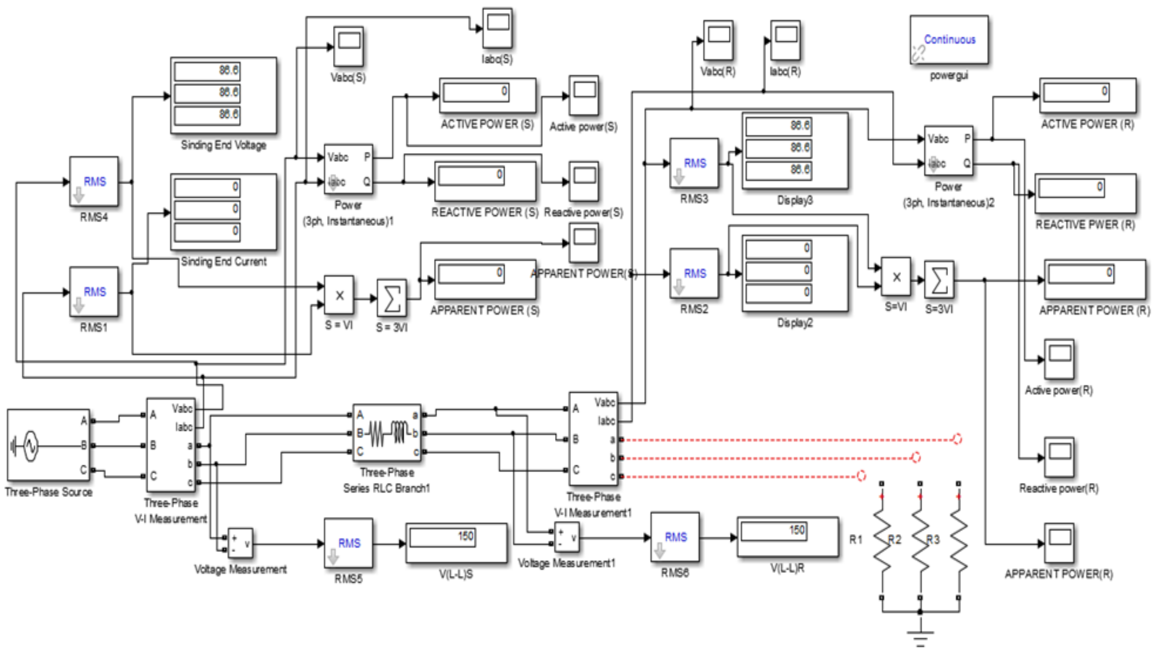

Figure 4. MATLAB Simulink for single transmission line without load without phase shift

B. A double transmission line according to the following scenario:
- No-Load line without phasing
- Load line without phasing
- No-Load line with phasing
- Load line with phasing

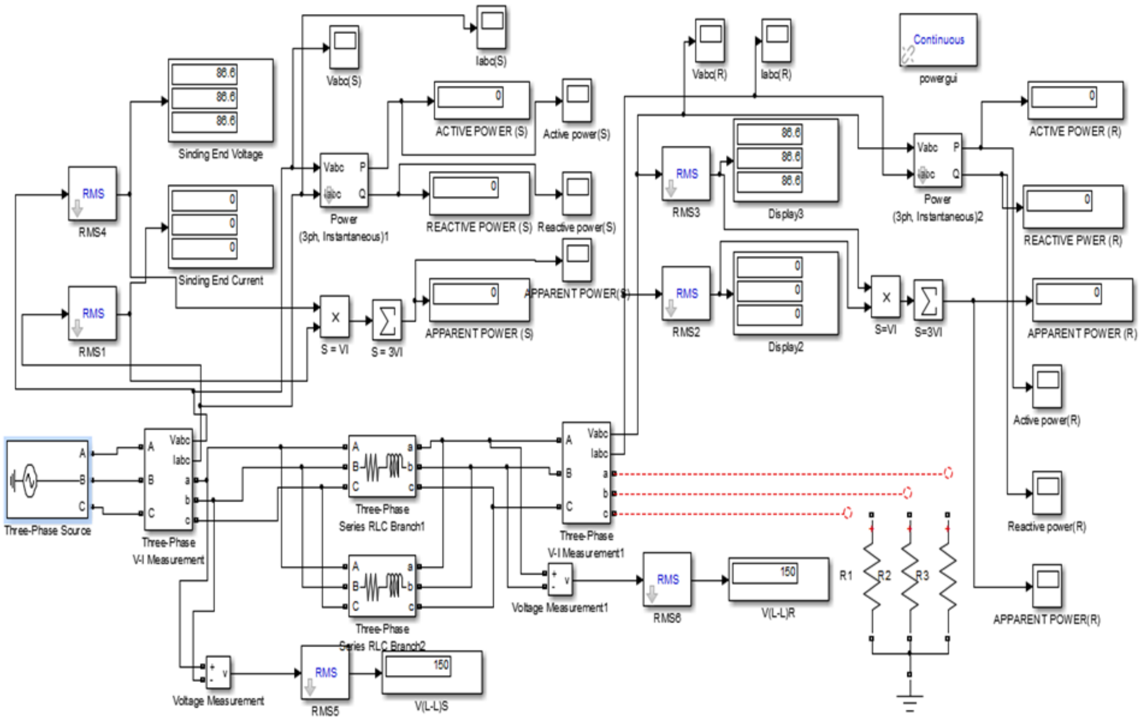

Figure 5. MATLAB Simulink for double transmission line without load without phase shift

3. RESULTS AND DISCUSSION

This section explains the results of the research and, at the same time, provides the needed comprehensive discussion. Results can be presented in figures, graphs, tables, and others that help the reader understand the whole principle. Therefore, the discussion will be illustrated in the following sub-sections.

3.1. Single transmission line

This table displays the experimental results obtained by using a simulator of energy transmission line type SLE/2 without and with load with phase shift. As well as the results obtained by using MATLAB simulation for a single transmission line. The analysis, comparison, and impact of using a phase-shift transformer are discussed in Table 4.

Notes on the No-Load test results:

- In the no-load test, the transmission line parameters are R-L in series and stray capacitance in parallel. A shunt capacitor is connected to the transmission line, which increases the receiving voltage, and if the receiving voltage is greater than the sending voltage, the power will return to the sending end, causing what is known as the Ferranti effect (the generator becomes a motor, resulting in severe damage). So as a result of that, it will eliminate the capacitor effect.
- Note that this effect does not appear in the table values above because, at the time of the experiment, the capacitance was not connected to the transmission line (the sending voltage is greater than the receiving voltage). But if the stray capacitances were connected, the long no-load line would have shown a slight increase in the arriving voltage. It can also be noted that the effect of the phase shift in the no-load test is to increase the receiving and sending end voltages while decreasing the drop voltage in the transmission line.

Table 4. Sending and receiving end without load with phase shift and with load with phase shift

Point	Value of experiment without load with phase shift		Value of MATLAB without load with phase shift		Value of experiment with load with phase shift		Value of MATLAB with load with phase shift	
	Sending	Receiving	Sending	Receiving	Sending	Receiving	Sending	Receiving
V_{ph1}	107.2 V	107.1 V	107 V	106.2 V	104.1 V	102.2 V	103.9 V	102 V
V_{ph2}	105.9 V	105.5 V	106.5 V	106 V	102.5 V	100.2 V	103.2 V	100.7 V
V_{ph3}	108.3 V	107.8 V	108.2 V	107.3 V	104.8 V	100.2 V	104.5 V	100.6 V
V_{L1-L2}	185.3 V	185.1 V	185 V	185.3 V	179.3 V	175.6 V	180.4 V	176.3 V
V_{L2-L3}	185.5 V	185.2 V	185.6 V	185.4 V	180 V	176.8 V	181 V	176.9 V
V_{L3-L1}	185.3 V	185.1 V	185 V	185.3 V	179.1 V	176.0 V	180.1 V	176.1 V
I_{ph1}	0.023 A	0 A	0 A	0 A	0.145 A	0.14 A	0.1411 A	0.1411 A
I_{ph2}	0.022 A	0 A	0 A	0 A	0.144 A	0.142 A	0.1411 A	0.1411 A
I_{ph3}	0.023 A	0 A	0 A	0 A	0.144 A	0.143 A	0.1411 A	0.1411 A
$P.F_1$	-0.057	1	0	1	-0.995	1	0.9993	1
$P.F_2$	-0.056	1	0	1	-0.995	1	0.9993	1
$P.F_3$	0	1	0	1	-0.995	1	0.9993	1
P_1	0.14 W	0	0	0	15 W	14.1W	14.6 W	14.33 W
P_2	0.1 W	0	0	0	14.9 W	14.2 W	14.6 W	14.33 W
P_3	0 W	0	0	0	14.8 W	14.7 W	14.6 W	14.33 W
Q_1	-2.4 VAR	0	0	0	-1.42 VAR	0	0.548 VAR	0 VAR
Q_2	-2.2 VAR	0	0	0	-1.56 VAR	0	0.548 VAR	0 VAR
Q_3	-2.4 VAR	0	0	0	-1.7 VAR	0	0.548 VAR	0 VAR
S_1	2.4 VA	0	0	0	15.06 VA	14.1 VA	14.66 VA	14.33 VA
S_2	2.3 VA	0	0	0	14.98VA	14.2 VA	14.66 VA	14.33 VA
S_3	2.4 VA	0	0	0	14.89 VA	14.7 VA	14.66 VA	14.33 VA

3.2. For double transmission line

This table displays the experimental results obtained by using a simulator of energy transmission line type SLE/2 without and with load without phase-shift. As well as the results obtained by using MATLAB simulation for a double transmission line. Table 5 discusses the analysis, comparison, and impact of using a phase-shift transformer.

Table 5. Sending and receiving end without load without phase shift and with load with phase shift

Point	Value of experiment without load with phase shift		Value of MATLAB without load with phase shift		Value of experiment with load with phase shift		Value of MATLAB with load with phase shift	
	Sending	Receiving	Sending	Receiving	Sending	Receiving	Sending	Receiving
V_{ph1}	87.4 V	87.3 V	87.6 V	87.2 V	85.72 V	86.0 V	85.53 V	85.72 V
V_{ph2}	86.3 V	86.2 V	86.6 V	86.4 V	84.28 V	84.1 V	84.83 V	84.28 V
V_{ph3}	88.1 V	88.1 V	88.9 V	88.7 V	86.78 V	86.81 V	86.23 V	86.78 V
V_{L1-L2}	151.7 V	151.1 V	151.8 V	151.0 V	148.2 V	149.0 V	147.9 V	148.2 V
V_{L2-L3}	151.5 V	151.3 V	151.4 V	151.1 V	148.3 V	148.3 V	148.0 V	148.3 V
V_{L3-L1}	151.0 V	150.9 V	151.0 V	150.7 V	148.4 V	148.8 V	148.3 V	148.4 V
I_{ph1}	0.037 A	0 A	0 A	0 A	0.12 A	0.1208 A	0.1208 A	0.12 A
I_{ph2}	0.035 A	0 A	0 A	0 A	0.12 A	0.1208 A	0.1208 A	0.12 A
I_{ph3}	0.036 A	0 A	0 A	0 A	0.12 A	0.1208 A	0.1208 A	0.12 A
$P.F_1$	-0.058	1	0	1	1	0.9993	1	1
$P.F_2$	-0.04	1	0	1	1	0.9993	1	1
$P.F_3$	0	1	0	1	1	0.9993	1	1
S_1	0 VA	0 VA	0 VA	0 VA	10.31 VA	14.316 VA	10.27 VA	10.31 VA
S_2	0 VA	0 VA	0 VA	0 VA	10.14 VA	14.316 VA	10.27 VA	10.14 VA
S_3	0 VA	0 VA	0 VA	0 VA	10.43 VR	14.316 VA	10.27 VA	10.43 VR

Notes on the no-load test results:

- The results of the double transmission line no-load test were the same as those of the single transmission line no-load test. However, the double transmission line reduces the line reactance by half, lowering the drop voltage and increasing efficiency. Whereas in a double transmission line without phase shift, the voltage remains constant.

Notes on load test results:

- In the double transmission line, the obtained results were the same as with the single transmission line no-load test. However, the double transmission line led to a reduction in the line reactance by half, which reduced the drop voltage and increased efficiency (efficiency would be higher, so two lines in parallel are advantageous compared with a line having conductors of double section). Whereas in a double transmission line with phase shift, the voltage is constant.

3.3. The comparison results between the single and double lines

Table 6 shows the comparison of the results between single and double transmission lines. Table 6 interpretation is a mirror image of the obtained results in two cases: single and double transmission lines. On the other hand, the table shows a clear comparison of the results of the two lines. Note that the comparison takes into account the Ferranti effect, drop voltage, power transfer, and the impedance of the line. Generally, the table shows that the double line has higher efficiency because it has a lower impedance than the single line, which gives it more transfer power.

Table 6. Comparison of the results between single and double transmission lines

Cause	Single transmission line				Double transmission line			
	Ferranti effect	Drop voltage	Power transfer	The impedance of the line	Ferranti effect	Drop voltage	Power transfer	The impedance of the line
Without phase shift without load	Happen	Bigger	Less	Bigger	Happen	Less	Bigger	Less
With Phase shift with load	Does not happen	Bigger	Less		Does not happen	Less	Bigger	
With phase shift without load	Happen	Bigger	(No-load) No power		Happen	Less	(No-Load) No power	
Without phase shift with load	Does not happen	Bigger	Less		Does not happen	Less	Bigger	

4. CONCLUSION

We can conclude that the following were discovered after studying and examining all possible scenarios for transferring electrical power from the source to the end-user, assuming the presence of one or two lines on the side of the electrical power transmission line, and using the MATLAB software and the experimental equipment of the energy transmission line type SLE/2 at Al-Balqa Applied University (BAU): The phase shift affects the voltage at the receiving end and the sending end, and in general, the voltage drop at the transmission line will be decreased. i) On the other hand, the phase shift will decrease the losses at the receiving end of the transmission line, ii) The overall efficiency of the system will improve when the phase shift is tuned, iii) Under the same conditions, power losses on the single-line transmission line will be higher than on the double-line transmission line, iv) The line reactance is affected by the use of a double line since the reactance will be decreased to 50% of the base value of the single-line transmission line, v) A double-line system will introduce capacitors at the transmission line, and vi) In the no-load scenario, the Ferranti effect will be shown on the transmission line sides, this problem is solved by adding compensator reactances.

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