Abstract—the energy demand all over the world is increasing rapidly with the passage of time. In Pakistan, the demand and supply equation is almost reversed. The short fall has reached up to 5000 MW. The Pakistan Electric Power Company (PEPCO) is currently facing the generation shortfall. The transmission lines are already working on full load/over load condition. National Transmission & Dispatch Co. (NTDC) is supplying power to PEPCO and working as sole Transmission System Operator (TSO) in the country. In this worst scenario, the NTDC has to supply the electric power to Karachi Electric Supply Company (KESC) to meet their demands.

The main objective of this research work concentrates to deal with developing methodology/strategy using Phase-Shifting Transformers (PST) to control power flow between NTDC and KESC.

Index Terms—Power Flow Control, Phase Shifting Transformers (PST), Interconnections, Power System Stability and FACTS Devices

Karachi Electric Supply Company (KESC) is borrowing electricity from PEPCO through National Transmission and Dispatch Company (NTDC) working as Transmission System Operator (TSO), here the problem starts. The privatization of KESC has also worsened the already existed problem. They do not produce their own electricity according to their demands and rather import relative low-cost electricity from NTDC. KESC and NTDC have agreed for the supply of 600 MW.

In some cases up to 810 MW power export from NTDC system has also been recorded/observed, which causes the load shedding in the distribution companies (PEPCO/DISCOs) and also increases the burden on the NTDC transmission network and causes the transmission network congestion; as most of the generation companies lies in the eastern and southern part of the country. This practice has endangered the stability of the system in company with thermal overloading of the transmission network and resulted in heavy volumes of receivables.

The underlying answer to the above ins and outs is:
1. KESC Bridges present supply & demand gap and cater for future growth by adding new power plants
2. Focus on alternative Energy Projects based on Wind, Solar, and Biomass etc. to be envisaged.
3. Reduction of Transmission and Distribution losses
4. Planning & Development of Transmission Systems for evacuation of power from new generating plants
5. Curtailment of over loads/ strict power flow policy and saving of power

This research work focuses on point no. 5 i.e. investigation to devise a strategy in this deregulated market to follow the strict power flow policy.

I. LITERATURE SURVEY

The electricity network is constituted from network components. If any component gets congested its effect is felt by the system and the network is overburdened and is stressed to its limits [1]. The overburdening of transmission line or transformer might be the reason for this very bottleneck. Different methods can be used for the relief purpose which includes curbing pile of loads, use of tap changing transformers and Phase-Shifting Transformers. The removal of the overloaded component from the system might solve the problem but there is possibility than it can comprehend the problem [2].

It is normal practice that every organization wants to maximize its assets utilization. Similarly, they want to operate the transmission networks beyond their design parameters. The power flow management techniques are employed within the power system that could ascertain the cost-effective, dependable and secure progression of the system.
The active power flow in transmission networks necessitates the skillful embark upon to avoid congestions and enhancing the transmission capacity [3]. For this purpose Flexible alternating current transmission systems (FACTS) devices may be employed. However, the entire line impedance might be modified animatedly [4]–[6], however, it is costly solution.

The prospective of this technology is centered on the likelihood of controlling the route of the power flow and the ability of inter-connecting systems to exchange power, giving the leeway of restriction on the amount of active power out flow amid these utilities [7].

II. INTERCONNECTIONS

Different grids are connected to each other through tie-lines to form a regional grid. Different regional grids are further connected to form a national grid.

The demand and generation clusters can be created by interconnecting distinct utilities at high voltage level. There are a number of supplementary gains in addition to economic rewards which includes but not limited to the following:

• The bulk power is efficiently transferred from generation to load centers.
• A very good benefit of interconnecting system is that we select the cheapest sources from the power pool according to our demand needs.
• The transmission assets are efficiently utilized making the overall operation of the system more secure and reliable as compared to singular units and brings diversity by integrating all the peer groups i.e. generation and demand.
• The interconnected systems brings the overall cost to low level as the additional generation of one part of the system could be transferred to the areas with lower generation in such a way that less spinning reserves are needed for the system.
• When transmission systems are operating independently they have their identifiable frequency response to the variations in demand. However, when they are interconnected, they overall reaction require solitary to tie with the premier of the individual necessities of the system to overcome the prevalent loss of generation in contrary to their totality response.

There are three types of interconnection AC Interconnection, DC Interconnection and Hybrid AC/DC Interconnection.

A. Figure: Types of interconnections

III. POWER FLOW UNDER STEADY STATE CONDITION

For the purpose of understanding, now we consider the lossless transmission line (resistance is negligible), 'Vs' are the sending side voltages and 'Vr' are likewise the receiving side voltages & 'ф' is the angle amidst them and 'x' is the line reactance.

B. Figure: Sending & Receiving end Voltage Profile

The real and reactive power flow will be as under:

\[ S_s = P_s + jQ_s \quad (1) \]

\[ I = \frac{V_s - V_r}{jx} \quad (2) \]

\[ I^* = \frac{V_s^* - V_r^*}{-jx} \quad (3) \]

Inserting these values into equation-(1), results into:

\[ S_s = \frac{V_s(V_s^* - V_r^*)}{-jx} \quad (4) \]

\[ V_r = |V_r| \angle 0^\circ \quad (5) \]

\[ V_r^* = |V_r| \quad (6) \]

\[ S_s = P_s + jQ_s = \frac{|V_r||V_r|}{x} \sin \alpha + \frac{1}{x} (|V_s|^2 - |V_s||V_r| \cos \alpha) \quad (7) \]

\[ P_s = \frac{|V_s||V_r|}{x} \sin \alpha \quad (8) \]

\[ Q_s = \frac{(|V_s|^2 - |V_s||V_r| \cos \alpha)}{x} \quad (9) \]

Similarly, at receiving end; we can drive the expression as:

\[ S_R = P_r + jQ_r = V_rI^* \quad (10) \]

\[ P_r = \frac{|V_s||V_r|}{x} \sin \alpha \quad (11) \]
C. Figure: Parallel Transmission Lines Load Sharing

These equations show that the power flow through the line can be controlled by three ways i.e. alteration of the knot voltage, the impedance midst nodes and the angle amongst terminal voltages.

IV. POWER FLOW IN PARALLEL PATH

Consider a very simple case of power flow figure- C, through two parallel paths (possibly corridors of several lines) from a surplus generation area, shown as an equivalent generator on the left, to a deficit generation area on the right. When not control measures are exercised, the power flow undergoes the natural path i.e. the lower the impedance of line the greater will be the transmission. Apart from ownership and contractual concerns regarding the allowable limits of power for the transmission lines, the probability that the line with lesser impedance may turn out to be over encumbered and in this manner set a limit on load ability of both alleyways despite the fact the line with greater impedance is still under loaded.

VI. FACTS DEVICES

FACT devices works on the principle of altering one or more parameters as described in the below figure-D:

D. Figure: FACT devices working Principle

The basic applications of FACTS-devices are:
- Escalation of transmission competence
- Power flow regulator
- Voltage control
- Reactive power reparation
- Stability enhancement
- Power quality upgrading
- Power acclimatizing
- Flicker vindication

When considering the applications of these devices; prerequisites and paybacks are to be analyzed to substantiate the expenses for new multifaceted device.

VII. POWER SYSTEM STABILITY

In tangible world, the electrical power system is susceptible to abnormal conditions like faults, transients etc. They must be mended as soon as possible otherwise the stability of the whole system is endangered.

Power System Stability; in general terms be defined as its ability to return to normal or stable condition after has been wide-open to some form of disturbance (s).

The ability to exchange the energy among distinct system as per their requirements accounts for the power system stability.
Therefore, for the improvement of power flow; the system limitations are to be essentially described and cultivated [8].

Sometimes, the power limit is also interpreted as “Stability” because to have the maximum functioning of the system, it should be proficient enough of supplying maximum power without instigating instability [9].

**E. Figure: Locus of Stability Curve**

![Locus of Stability Curve](image)

It should be noted that the maximum power as obtained from the circle diagram cannot be realized in practice, since this would require an uneconomically large amount of reactive power to be supplied by the side of the receiving terminal so that the receiving-end voltage could be kept constant. It can be controlled by the application of load tap changers, static var compensators and a-symmetric phase shifting transformers [10].

If there are synchronous machines at both ends of a transmission line, the power limit is set by the ability of the machines to stay in synchronism with each other. This limit is called the (synchronous) stability limit [11]. The steady-state stability limit may be defined as the maximum power that can be delivered without loss of synchronism when the load is increased gradually and the machine terminal voltages are adjusted by manual control of excitation. Similarly, the transient stability limit may be defined as the maximum power that can be delivered without loss of synchronism following a large disturbance such as a system fault and its subsequent clearing.

**VIII. PHASE-SHIFTING TRANSFORMERS**

The compulsion to control the flow of power sprinkled when the areas of maximum asset deployment and economic benefits were studied. Then high-voltage systems were built and layered over home-grown systems and declared the standard of certain set of high-voltage transmission voltage echelons. In our time, to exchange the electrical power over large detachments the high-voltage power grids are connected to enhance the trustworthiness of the power supply. Resultantly, technical hitches could arise endorsed to so many reasons such as dissimilarity in power generation yield and power demand can lead to possible shattering system collapse and they must be sidestepped.

Strive for the fragmentary strive for better-quality AC network, the Phase shifting transformers (PST) are indispensable. Amassed extents of transmitted energy shove the networks to the perimeter of operational limits, aggregating the risk of network instability. PSTs are a lucrative means to safeguard steadfast and proficient power flow control in encumbered transmission network.

Phase shifting transformers safeguard transmission lines and HV equipment from thermal overload, improve transmission system stability and control the power flow between different networks involving parallel paths whether they are over stretched overhead lines or cables.

It is a distinctive form of a 3-phase utility transformer and can be comprehended by combining two transformers i.e. one winding arrangement connected in series with a line and the other in shunt. The shunt winding is furnished with a tap changer. The windings of this exciter transformer are connected in such a way that the difference of two phases is inserted into the third phase which results in producing phase-quadrature voltages on its secondary side. This voltage is then nourished into the secondary windings of the series transformer. Thus the accumulation of small, phase-quadrature voltage machineries to the phase voltages of the line crafts phase-shifted output voltages devoid of any appreciable change in magnitude [12].

**F. Figure: Quadrature Voltage Injection Illustration**

![Quadrature Voltage Injection Illustration](image)
IX. OPERATING PRINCIPLE OF PHASE SHIFTING TRANSFORMERS

The functionality of PST can be understood by considering it as transformer having two portions one is an ideal transformer with 1 ratio (symmetric) and other portion varies the angle. The type of PST in which voltage is also varied is called Asymmetric Phase-Shifting Transformer. The angle is varied between its source (primary) terminals and load (secondary) terminals. So, if it has to increase the power flow the load angle has to be greater than the source terminal called advance phase shift and vice versa is true and termed as retard phase shift. The PST accomplishes its function; it adds or subtracts the quadrature voltage in the source voltage. We are using symmetric version of the said transformer therefore this will be described in the literature under review.

G. Figure: Phase Advance/Retard Demonstration

X. PROPOSED METHODOLOGY

In this research work, the transmission line balancing current theme is used to balance the overall power on the interconnected system. A better solution is to install a phase-shifter in an appropriate location in the transmission grid [13], [14]. The principal use of phase-shifters is at major inter-tie buses where the control of active power exchange is especially important [15].

In the contemporary scenario, the phase-shifting transformers made possible to use the lost capacity of the system; hence the systems which are swiftly being overloading the exploitation of available network capacity is conceivable. The phase-shifting transformer, principally change the effective phase angle amidst the input and output voltages where it is installed, thus effect the amount of active power that is being transferred through the said path.

XI. MODEL NARRATIVE

By carefully investigating the single line diagram of the interconnecting grid, we came to the conclusion that there is already stepping down transformer i.e. 500/220 kV installed at the subject grid station i.e. NKI Sub-station and KESC is supplied from this grid-station by two 220 kV transmission lines. One connects at Baldia 220 kV Grid Station and the other at KDA-33 Grid Station.

H. Figure: Geographical Location N.K.I

Therefore, we concluded that we have to use the transformer of 220 kV voltage rating. The next step was to calculate the power rating of the phase shifting transformer. For this very reason, the phase angle has to be known. This was the very complex question to answer. Because, it involves so many parameters; the power retard level, the distance relay settings, the characteristic angle of the line, the characteristic angle of the distance relay etc.

The actual data of the lines were used to get the results, which are tabulated in table 1 & 2 below:

Table-1: 220 kV NKI-BALDIA Line Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>13.326 Km</td>
</tr>
<tr>
<td>+Ve Sequence Reactance</td>
<td>0.4411 Ω</td>
</tr>
<tr>
<td>+Ve Sequence Resistance</td>
<td>4.2094 Ω</td>
</tr>
<tr>
<td>Zero Sequence Reactance</td>
<td>4.7014 Ω</td>
</tr>
</tbody>
</table>

Line angles can be calculated as:

\[ \alpha_+ = \tan^{-1}\left(\frac{X1A}{R1A}\right) = \angle 84.0' \]

\[ \alpha_0 = \tan^{-1}\left(\frac{X0A}{R1A}\right) = \angle 78.5 \]

Table-2: 220 kV NKI-KDA-33 Line Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>29.093 Km</td>
</tr>
<tr>
<td>+Ve Sequence Reactance</td>
<td>0.963 Ω</td>
</tr>
<tr>
<td>+Ve Sequence Resistance</td>
<td>9.1905 Ω</td>
</tr>
<tr>
<td>Zero Sequence Reactance</td>
<td>10.264 Ω</td>
</tr>
</tbody>
</table>

Line angles can be calculated as:

\[ \alpha_+ = \tan^{-1}\left(\frac{X1A}{R1A}\right) = \angle 84.0' \]

\[ \alpha_0 = \tan^{-1}\left(\frac{X0A}{R1A}\right) = \angle 78.5 \]

Therefore we take the maximum inclination angle as 80° for the PST as maximum phase shift angle limit.

Now calculate the size of the PST considering its economic cost and the base line of the contractual limit is found from the historic trend of power flow from NTDC to KESC as 600 MW (the minimum as 350 MW and the maximum as 810 MW).
From the above discussion, it can be concluded that the phase shift angle will be 78.5°.

The size of the Phase Shifting Transformer is calculated by the below equations – r & s:

\[ P_{\text{sys}} = 3 \times V \times I \quad \text{Equation (18)} \]

However, in our case; we take it from the contractual limit i.e. 600 MW and the rated design power, which determines the size of PST, becomes:

\[ P = 3 \times V \times I = P_{\text{sys}} \times 2 \times \sin \left( \frac{40}{2} \right) \quad \text{Equation (19)} \]

\[ P = 600 \times 2 \times \sin (40/2) = 410 \text{ MVA} \]

I. Series Unit Rating - 410 MVA
II. Exciter Unit Rating - 410 MVA

The next job was to integrate all the pieces of this power system to obtain the results. The circuit model is given below to give you the insight of the model, there is 500 kV source, the next is step-down transformer to level of 220 kV connected to the source side of PST and the two transmission lines of 220 kV are connected to the load side of the Phase shifting transformer.

XII. DEMONSTRATION

In order to observe impact of phase shift on power transfer, the phase shift is decreased from zero to 78° (tap 10). This is performed by sending ten pulses to down the tap and then 10 pulses to up the tap to validate the stability of the model. If we don't send the pulses to 'up' tap then it will deliver the power at the minimum level that is 360 MW and if we bypass the PST it will not alter the system parameters.

XIII. RESULTS

The repercussion is compendium as:

- Trace-1: Shows the Tap Position
- Trace-2: Shows the Power transfer w.r.t altering phase shift
- Trace-3: Shows the Phase Shifting Angel
- Trace-4: Shows the p.u. current
- Trace-5: Shows the p.u. Voltage

XIV. CONCLUSION

The solution is proposed on the basis of above discussion that the power flow from NTDC to KESC can be restricted at the level of 600 MW i.e. at the contractual limits. Moreover, this solution is cost effective along with environmental benefits.

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