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Transmission System Performance Improvement through Reactive Power Compensation

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Abstract: Transmission lines carry bulk power from generating stations to load centers. Utility regulations limits substantial amount of voltage drop in any network to ensure efficient and reliable operation of interconnected grid. Reactive power compensation is essential for safe and efficient performance of modern power systems. Improperly managed reactive power flows result in poor voltage regulation, consumer dis-satisfaction, increased power losses and sometimes long duration system outages.

In this paper, the simulation studies are carried out on 132kV and 66 kV networks of Hyderabad Electric Supply Company (HESCO) to analyze bus voltages and system efficiency. Voltages at some of the 132 kV buses are observed below accepted lower limits of 5%. Even some of the buses were having voltage less than 90% of the rated voltage. Suitable reactive power compensation through fixed capacitors is proposed and benefits are confirmed through simulation of modified network as voltages of all the buses have significant improvement. Power losses in the system are also reduced from 5.39% to 4.24% through proposed capacitors.

Keywords: Reactive power compensation; Shunt capacitors; Voltage regulation; Power losses; HESCO.

1. INTRODUCTION

Over the years, the power consumption is increasing day by day in all over the world, due to population growth, shifting of public to metropolitan areas, switching to luxury life and industrial growth. To meet the predicted and un-predicted load growth, countries are more focused on installation of new power plants and associated transmission network for delivering electric power to the tail end. For safe dispersal of electric power from source (normally primary grids) to the load centers, stable transmission network is required. Despite a good transmission network, there are some serious problems relating to voltage, power factor and line losses owing to long line lengths and over loading (Dixon, *et al.*, 2005).

Transmission of electric power has to take place in the most efficient way. Generation and active power demand is basic requirement for a power system operation. Frequency of the system is measure of balance between load and supply. Reactive power balance is also as important as active power. Reactive power is directly proportional to voltage and therefore Reactive Power Compensation (RPC) is required to improve system bus voltages (Johnson, *et al.*, 2009). Additionally power factor at different sections of the power system is improved resulting in reduced technical losses.

Power system network simulation is a tool for network planning and Power System Simulation Engineering (PSS/E) software is one of the software packages used for transmission system planning and contingency analysis (Uqaili, *et al.*, 2014). It is composed of a comprehensive set of programs for studies of power system transmission network and generation performance in both steady-state and dynamic conditions. Two primary simulations are used, one for steady-state analysis and one for dynamic simulations. Power flow analysis under steady state and contingency analysis are highly beneficent for planning of electric utility (Sahito, *et al.*, 2015).

Power system in Pakistan comprises of different generation companies (GENCOs), one National Transmission and Dispatch Company (NTDC) and ten distribution utility companies (DISCOs) (Halepoto, *et al.*,2015). The National Electric Power Regulatory Authority (NEPRA) is responsible for setting different codes for proper operation of electric power system in Pakistan. Clause O.C 4.9.1 of NEPRA Grid Code bounds DISCOs and large industrial consumers to maintain power factor above 0.9 during steady state operation. It also states that bus voltage at the point of interconnection to NTDC must be maintained within a bandwidth of +8% and -5% of rated voltage under normal conditions. In case of a contingency (N-1) operating condition, the allowable limit is ±10% of nominal system (NEPRA., 2005). Hence it is important for DISCOs to have some reactive power compensation techniques and capacitors are considered as most efficient method (Sahito, *et al.*, 2014). Capacitors are installed in almost all sections of the power system

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from generation bus to distribution system. Series and shunt capacitors are installed to improve voltage regulation. Power electronic control for capacitor switching is employed to obtain smooth and efficient control for RPC.

In this research work, 132 kV and 66 kV network of Hyderabad Electric Supply Company (HESCO) are selected for performance analysis. PSS/E software is used to model and simulate the existing network. Bus voltages are analyzed and affected areas are identified. RPC of the system is proposed through fixed shunt capacitors. Proposed system is simulated and results are discussed in details. Special focus is given to MIRPURKHAS and surrounding areas, where supply outages and frequent tripping of transmission network were observed regularly by network operators.

Section 2 describes concept of RPC and use of capacitors is explained with a simple two bus system focusing on improvement in bus voltages and power losses. Individual and group compensation is also explained in this section. Network details of the transmission network of HESCO are given in section 3. Section 4 contains simulation results for bus voltages. Affected areas are identified and proposed RPC through shunt capacitors is also analyzed in this section. Section 5 describes power loss reduction and its economic benefits. Research work is concluded in section 6 and suggestions for improvement and future work are also part of this section.

2. REACTIVE POWER COMPENSATION

Transmission line capacity is dependent on both active and reactive power flow. Higher the amount of reactive power flowing through a transmission line, lower will be its capacity. As reactive power flow is directly proportional to voltage drop therefore higher the reactive power flow in lines, more will be voltage drop resulting in lower bus voltages. Low voltage at distribution system buses will result in low voltage supply to consumers. Therefore reactive power is considered like highway on which active power flows; proper reactive power in the system results in proper real power flows in the system. Poor load power factor will cause higher reactive power requirement resulting in excessive current flows and power losses.

The management of reactive power in any electric power network can be defined as volt-ampere reactive (VAR) compensation. RPC can help to transmit the reactive power on transmission network up to certain limit (Farhana, *et al.*, 2013). A stable transmission line can dispatch the proper power to consumer end to fulfill the demand of the area. Increasing fossil fuel prices, utility operation costs and competition demand, for most efficient power system network. Thus Reactive power demand and supply has become an important consideration in modern power systems. In Alternating Current (AC) power systems, it has always been a challenge for obtaining the balance between a minimum volume of reactive power flow (to maximize capacity for active power flow) and a sufficient amount of reactive power flow to maintain a proper system voltage profiles (Karcius. *et al.,* 2013). The reliable and economic use of electric power depends on an availability of sources for leading and lagging reactive power that can be appropriately dispatched to the system. For system operation, balance between absorbed and injected reactive power is important. Consumers of reactive power include large induction machines, electric arc furnaces, overhead transmission lines and transformers. On the other hand synchronous generators, synchronous condensers, underground cables, lightly loaded overhead transmission lines and capacitors are considered as sources of reactive power (Yuan. *et al.*, 2008).

Capacitors are considered as most economical source of reactive power compensation and can be connected in series and parallel (Virk. *et al*, 2013). Series capacitors have no impact on power factor and contain protection issues as all the load current has to pass through capacitors. Shunt capacitors are widely used for power factor correction and voltage regulation in power system since their first use in 1920. Modern power systems use power electronic switches to control switching of the capacitors. Power electronic switches are fast acting and provide efficient control on RPC in dynamic system operation. Use of power electronics switches to control dynamics of transmission system is called Flexible Alternating Current Transmission (FACTS) (Rabiee. *et al.*, 2009).

To understand the concept of RPC through shunt capacitors, simple two bus system is considered as shown in **(Fig. 1(a)).** Power grid is represented by source connected to bus 1, whereas load of 100kW at 0.74 lagging power factor is connected to bus 2. Both buses are connected through a transmission line having impedance $Z = (10 + j\,40)\ \Omega$. Source voltage is considered constant at $11\angle 0^0$ kV. When load current (I) flows through transmission line, voltage drops in it and is given as:

$$V.D = IZ \qquad (1)$$

Therefore voltage at bus 2 is $10.56\angle$-1.53^0 kV, which is lower as compared to bus 1 voltage. Resistance (R) of the transmission line is responsible for power losses P_L in the transmission line as:

$$P_L = I^2R \qquad (2)$$

Shunt capacitors of 88.25 kVAR are selected for RPC of the two bus system under consideration. Two different cases are analyzed with respect to capacitor placement. **(Fig.1(b))** shows that capacitors are connected at Bus1 near the source whereas **(Fig.1(c))** indicates the case where capacitors are connected to Bus 2 near the load. Voltage at Bus 2 and power losses in transmission line for three cases are compared in **(Table 1)**.

Table 1. Voltage and Power Losses Comparison for Two Bus System

Case	Voltage at Bus2 (kV)	Power Losses (kW)	Reactive Power from source (kVAR)
No RPC	10.56	1.64	97.45
RPC at Bus 1	10.56	1.64	9.20
RPC at Bus 2	10.89	0.84	6.02

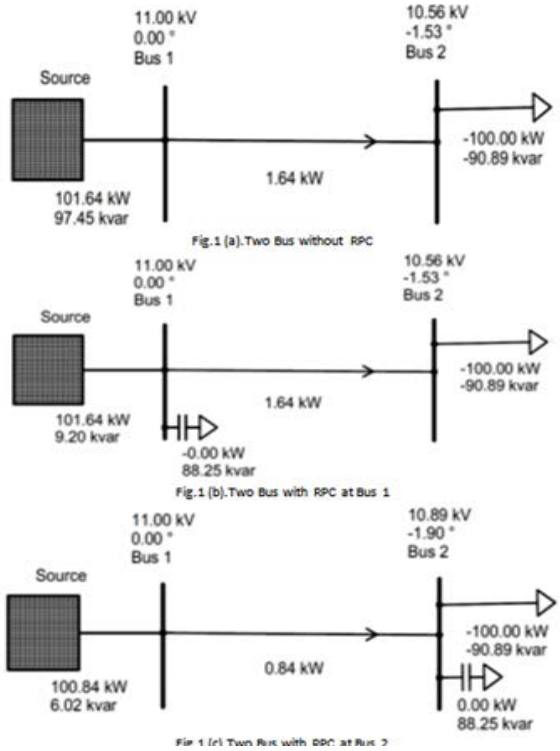


Fig.1. Reactive Power Compensation Through Capacitors

It is observable from analysis that RPC at bus 1, near the source neither improve bus 2 voltage nor reduce power losses in the transmission line. It reduces the reactive power absorbed from source as capacitors provide 88.25 kVAR of the reactive power. When capacitors are connected near the load at bus 2, significant improvement in bus voltage and reduction in power losses is observed. Therefore local compensation of reactive power is considered best, instead of providing the same through faraway sources (El-Moursi. *et al.,* 2005). Capacitors have no effect on system after their point connection.

When considering large number of loads, RPC is provided either individually or in groups of loads. When each load is compensated separately, it is called individual compensation and is shown in **(Fig. 2(a)).** It results in accurate and most effective compensation but has higher initial cost. Another approach is to group different loads together and then compensate with a larger capacitor bank as shown in **(Fig. 2(b))**. It is called group compensation and is more economical as compared to individual compensation.

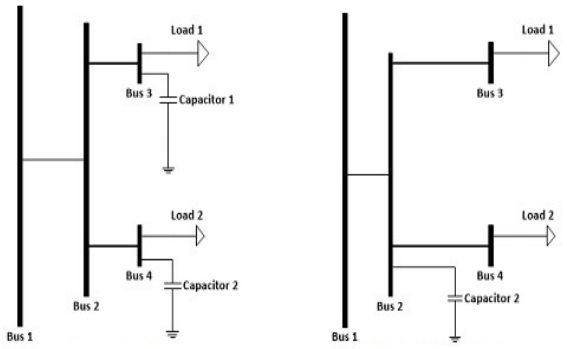


Fig. 2. Capacitor Compensation Types

In Pakistan, Industrial consumers are penalized for low power factor; therefore they use automatic switched capacitor banks to improve their power factor. Residential and commercial consumers are free of such penalty and charged for their active energy consumption only. Most of the residential and commercial loads are inductive in nature and have low power factor. Examples are compact fluorescent lamps, electric fans and induction motors for water lifting. Therefore power factor of the distribution system is poor and utility has to improve it at its end. Shunt capacitors are installed at distribution substations and distribution feeders.

3. SYSTEM DESCRIPTION

Hyderabad Electric Supply Company (HESCO) is one of the ten distribution utility companies of Pakistan. It supplies electricity to about 952,263 consumers of residential, commercial, industrial and agricultural types, equally distributed in rural and urban areas. Maximum demand is nearly 1,100 MW in summer and 800 MW in winter seasons. Transmission network of HESCO consists of two voltage levels i.e. 132 kV and 66 kV. **(Table. 2)** shows number of grid station and length of transmission lines for 132 and 66 kV networks. HESCO. Line length of 132 kV network is more than twice that of 66 kV. This is a design advantage as high voltage means less current and thus less voltage drop. But 30% of 66 kV network also needs to be upgraded to 132kV for better system performance.

Table 2.Transmission Network of HESCO

Network Voltage (kV)	No. of Substations	Line Length (km)
132	50	2067
66	21	975
Total	71	3042

HESCO transmission network is supplied mainly through NTDC network. For simulation of the network, NTDC point of interconnections are represented by generating stations at Jamshoro and Dadu substations having total generation capacity of 835 MW. Six thermal power plants having total capacity of 195.8 MW are connected to 132 kV network as given in **(Table 3).** Wind farm of 100MW is also connected to 132 kV Jhampir & Noriabad grid stations. Additionally two power plants of total 19 MW capacity are connected on 11kV buses at Mir Wah Gorchani and Matli sub stations. Power supplied to neighboring distribution utility of Sukkur Electric Power Company (SEPCO) at two points is considered as loads at Qazi Ahmed and Dadu substation buses.

Table 3.Thermal Generating Stations in HESCO Network

Sr. #	Generating Station	Capacity (MW)	Generation Source
1.	Kotri S.I.T.E	12	Gas
2.	Kotri G.T.P.S	105	Gas
3.	Thatta	18.8	Gas
4.	Lakhra	30	Coal
5.	Noriabad	10	Gas
6.	KaluKahar	20	Gas
Total		**195.8 MW**	

4. BUS VOLTAGE IMPROVEMENT

Whole transmission network of HESCO with generation sources and loads is simulated using PSS/E software. Simulation results show that some of the 132 kV buses have very low voltages. For example 132 kV MIRPURKHAS bus shown in **Fig.3** has a bus voltage of 122.307 kV (92.657% of the rated voltage). Here bus voltage is 7.343% less than rated voltage which is beyond acceptable limit of 5%. The bus voltages, active and reactive power flows associated with lines connected to MIRPURKHAS substation are also shown in **(Fig.3)**. Positive powers indicate outgoing powers whereas incoming powers are represented by negative. Bus voltage at 132 kV HALAROAD substation is 135.8 kV and there is drop of 13.5 kV in HALAROAD to MIRPURKHAS circuit only.

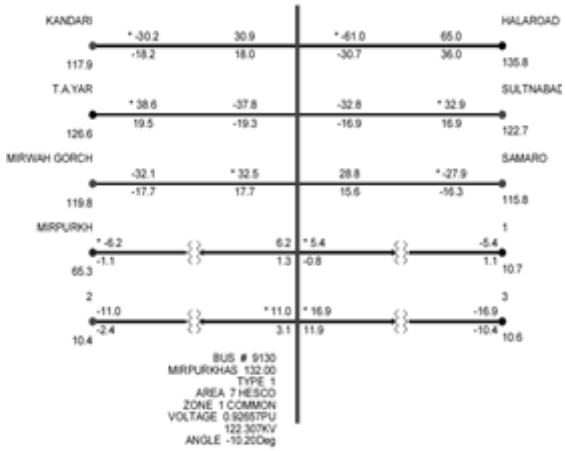


Fig.3. Simulation Diagram for 132 kV Mirpurkhas Substation Bus

132 kV Tando Allah Yar (T.A.YAR) and SULTANABAD substations are other sources for MIRPURKHAS substation having voltages of 126.6 and 122.7 kV respectively. There are four outgoing lines to 132 kV KANDARI, MIRWAH GORCH and SAMARO substations. All three substation buses have voltages less than 120 kV. SAMARO substation further supplies power to 132 kV NOUKOT and UMARKOT substations have bus voltage of 114.5 and 113 kV respectively. 66 kV Observed bus voltages indicate requirement of reactive power sources to compensate for its demand. Hence RPC is proposed through fixed capacitors of 144 MVAR to be installed at buses given in the **(Table 4).**

Table 4. Proposed Shunt Capacitors for Reactive Power Compensation in HESCO

Sr. #	Location	Capacity (MVAR)
1	132 kV MIRPURKHAS	18
2	132 kV SAMARO	48
3	132 kV SANGHAR	24
4	132 kV NAWABSHAH-I	36
5	SHAHDADPUR	18
Total		**144 MVAR**

Simulation network is modified to include proposed shunt capacitors for RPC. Simulation of modified network shows significant improvement in bus voltages for MIRPURKHAS – UMARKOT section as given in **(Table 5).** It is observed that bus voltage for MIRPURKHAS substation is improved from 122.3 to 133.8 kV which indicates 8.71% rise in bus voltage. Bus voltage for HALAROAD substation has further increased to 139.6 kV, which is 105.7% of the rated voltage and within allowable range of +8% above rated voltage. 36 MVAR previously supplied through HALAROAD-MIRPURKHAS transmission section is

compensated through proposed capacitors reducing its voltage drop from 13.5 kV to 5.8 kV. All bus voltages are in allowable range as a result of proposed RPC.

Table 5. 132 kV Bus Voltages for Mirpurkhas and Samaro Sections

Bus	Bus Voltage (kV)		Rise in voltage After RPC	
	Before RPC	After RPC	kV	%
HALAROAD	135.8	139.6	3.8	2.88
T.A.YAR	126.6	134.9	8.3	6.29
SULTNABAD	122.7	133.9	11.2	8.48
MIRPURLKHAS	122.3	133.8	11.5	8.71
MIRWAH GORCH	119.8	133.3	13.5	10.23
KANDARI	117.9	132.0	14.1	10.68
SAMARO	115.8	132.5	16.7	12.65
NOUKOT	114.5	131.6	17.1	12.95
UMARKOT	113.0	130.3	17.3	13.11

5. POWER LOSS REDUCTION

Shunt capacitors for RPC also improves power factor at different buses resulting in reduced current flows, and thus reduced power losses. Consider simulation bus diagram of MIRPURKHAS substation shown in **Fig.3** given above. Power losses of each line connected to the substation are calculated by adding input and output power mentioned on the line. For example active power sent from HALAROAD is 65 MW and power received at MIRPURKHAS substation is 61 MW, resulting in a loss of 4 MW. After proposed RPC, power loss in this line is reduced to 2.8 MW, (reduction of 1.2 MW). (**Table 6)** show power losses in existing and compensated systems for six 132 kV lines connected to MIRPURKHAS bus. Total power losses for considered six buses are reduced from 6.9 MW to 4.7 MW indicating a significant reduction of 2.2 MW. Reduction in power losses is due to increase in power factor and bus voltages resulting in less current flowing through lines.

Table 6. 132 kV Bus Voltages for Mirpurkhas and Samaro Sections

Line		Power Losses (MW)		
Substation	**Power Flow Type**	**Before RPC**	**After RPC**	**Reduction**
HALAROAD	Incoming	4.00	2.80	1.20
T.A.YAR	Incoming	0.10	0.00	0.10
SULTNABAD	Incoming	0.80	0.60	0.20
MIRWAH GORCH	Outgoing	0.40	0.30	0.10
KANDARI	Outgoing	0.70	0.30	0.40
SAMARO	Outgoing	0.90	0.70	0.20

Simulation of complete system with and without proposed RPC revels that total power losses are reduced from 61.9 MW to 48.7 MW respectively. Therefore 13.2 MW reductions in power losses is achieved through proposed RPC as shown graphically in Fig.4. Percentage power losses reduction is from 5.39% to 4.24%, indicating a significant decrease of 1.15%.

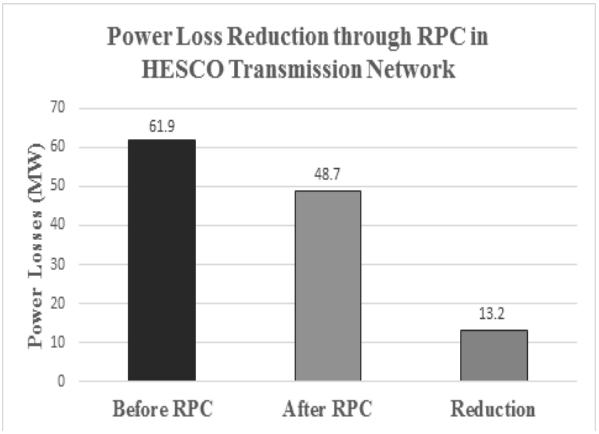


Fig.4. Power Loss Reduction through RPC in HESCO Transmission Network

After calculating reduction in power losses, respective reduction in Annual Energy Losses (AEL) are calculated as:

$$\mathbf{AEL=P_L*8760*F_{Loss}} \quad (3)$$

Where, P_L are power losses and F_{Loss} is loss factor.
Loss factor is calculated as

$$\mathbf{F_{Loss}=0.3*F_{Load}+0.7*(F_{Load})^2} \quad (4)$$

Where,F_{Load} denotes load factor.
By considering load factor of 60%, loss factor will be

$$\mathbf{F_{Loss}=0.3*0.6+0.7*(0.6)^2=0.432}$$

Reduction in Power Losses = 13.2 MW, Hence reduction in Annual energy losses will be

$$\mathbf{AEL= 13.2*10^6*(8760)*(0.432)=49.953\ MKwh}$$

Considering an average sell rate of Rs.14 per kWh, Total Annual Savings (TAS) will be

TAS= 49.953*14 =699.342 Millions Rs.

Although cost of capacitors is seldom justified on the basis of energy loss reduction (Farhana. *et al.,* 2013) but in this case sufficient savings is possible because of using fixed capacitors. Manual switching of the capacitors is proposed which saves cost for automatic switching control circuitry.

6. CONCLUSION

Aged transmission and distribution network, improper planning and reactive power management are contributors to high technical losses in HESCO. Improperly managed transmission network of HESCO cause unacceptable voltage drops and power losses. HESCO transmission network simulation using PSS/E software revels cause of poor system performance as

improper reactive power management. Hence for RPC, shunt capacitor banks of 144 MVAR are proposed to be installed at five different locations. Significant improvement of bus voltages in affected area is observed through simulation results of proposed compensation. Additionally 13.2 MW of Power losses in the network have also reduced. Estimated annual benefit through this loss reduction alone is nearly 700 Million Rupees. Fixed or manually switched capacitors banks improve performance of power system networks in Pakistan without worrying about cost for automatic capacitor bank control circuitry.

It is recommended to implement simulation based fixed capacitor banks for reactive power compensation in HESCO. These studies can be further extended for other parts of the country to improve efficiency of Pakistan power sector.

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