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Unbalanced Loading; An Overlooked Contributor to Power Losses in HESCO

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Abstract: Energy losses are hampering progress of the developing countries like Pakistan by putting extra financial burden that could have been used for development projects of the power sector. Electricity consumers are paying high energy cost despite of facing long duration load shedding and frequent small duration supply interruptions. Although electricity theft is considered as major cause of the losses but technical losses caused by aged distribution network and poor operation planning is also on higher side. Unbalanced loading caused by single phase loads supplied by three phase four wire system is an ignored source of power loss in distribution utilities of Pakistan, which is controllable by small investment on monitoring and line staff dedicated for load balancing.

In this paper, one of the distribution feeder in Hyderabad is selected for analysis of power losses caused by unbalanced loading. Exact data collection, modelling and simulation of the selected feeder shows high load unbalance. Balancing of the observed unbalanced loads result in power loss reduction of 62.8 kW amounting to an annual savings of Rs. 2.68 Million. It is recommended to HESCO and other distribution utilities in Pakistan to depute dedicated line staff for monitoring and balancing of the transformer loads to increase energy efficiency. Smart meter installation at all transformers will provide unbalance data for pre-set time intervals for balance analysis.

Keywords: Distribution system; Power losses; Unbalanced loading; HESCO.

1. INTRODUCTION

Power losses in distribution network are affecting performance of power sector resulting in financial loss and consumer dissatisfaction. Technical and non-technical losses are two broad categories for power losses. First is caused by current interacting with resistance of the system components (I^2R) (Sahito. *et al.* 2014) and second being related to administrative and commercial procedures. Electricity theft is considered as chief cause of non-technical losses. Technical losses cannot be completely eliminated but minimized by controlling the factors responsible for their increase such as poor power factor, unbalanced loading, over loading and improper joints.

Electricity consumers in Pakistan are facing long duration load shedding due to increasing energy prices caused by demand supply gap and high energy losses. Hyderabad Electric Supply Company (HESCO) is a distribution utility responsible for power distribution in lower part of the province of Sindh including the districts of Hyderabad, Badin, Mirpurkhas, Thatta, Matiari, Nawabshah and surroundings. The problem of energy losses is badly affecting performance of Pakistan's power sector in general and HESCO in particular.

Calculation of energy losses (E_{Loss}) in transmission and distribution systems follows a typical procedure of deducting the billed energy (E_{Billed}) from supplied energy ($E_{Supplied}$) as given in eq. 1. (Aguero 2012).

$$E_{Loss}=E_{Supplied}-E_{Billed} \quad (1)$$

Unbalanced loading and associated unbalanced voltages are the problems caused mainly by single phase loads supplied through three phase four wire low tension (L.T) network. Unbalance in current magnitudes/angles or both may be presented, depending on the supplied loads. Power losses increase with increasing degree of unbalance in system. Contribution of unbalanced loading in increased power losses is normally over looked by HESCO and other utilities in Pakistan. In addition to increased power losses, unbalanced loading may result in de-rating and damage of equipment such as transformers, motors and protection system.

Reduced efficiency, increased heating, reduction in effective torque and speed are some of the effects of unbalanced terminal voltages for induction and synchronous motors. Unbalance will cause reduced available capacities for overhead conductors, cables and transformers. Frequent tripping may result due to unbalanced currents as current in one phase may reach high magnitude resulting in overload tripping. System technical losses will change as current in different phases will change and are discussed in subsequent sections.

(Suman. *et. al.* 2012) used IEEE 16 bus system model for loss analysis using MATLAB®. They focused that load flow analysis will help to identify problems and developed a loss reduction plan. (Davoudi. *et al.* 2012) analyzed the unbalanced loading level at sub transmission level and concluded that unbalanced loading increases power losses and reduce transmission capacity.

This paper focuses on contribution of unbalanced loading in distribution network of HESCO. 11kV feeder is selected from HESCO network supplying residential

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and commercial consumers in city of Hyderabad. Modelled existing system is simulated to observe unbalance level and technical losses. The network is modified by balancing the loads on secondary side and modified network is simulated for power losses. Hence, contribution of unbalanced loading in total technical power losses is estimated through power loss reduction. Revenue loss due to unbalance loading is calculated and monitoring actions are suggested to improve system efficiency by reducing unbalanced loading and associated power losses.

Section 2 of the paper defines unbalanced loading and some of the factors used to identify degree of unbalance. Concept of power losses caused by unbalanced loading is explained in section 3. Section 4 contains detailed description of the selected feeder of HESCO network, its simulation results and discussions. Finally paper is concluded in section 5.

2. UNBALANCED LOADING

Distribution system is supplying a variety of consumer loads including single phase and unbalanced three-phase loads (Lin. *et al.* 2008). Modern countries have single phase laterals and transformers for supplying single phase loads. Single phase consumers in Pakistan are supplied by three phase four wire distribution system. Operation of these loads cause an unbalance operating state in distribution system. Apart from unevenly distributed single-phase loads, balanced three-phase loads may also cause temporary unbalance state due to open or short circuit fault. An unbalanced load may show up as different load current levels among phases, or same load current levels but different phase shift, or both (Reddy *et al.* 2012).

A three-phase four-wire system provides higher protection sensitivity for fault when neutral is grounded at multiple points. This multiple grounding is normally achieved at L.T poles in overhead distribution system. Current in neutral conductor (I_n) is termed as return current and depends on load unbalance. If I_1, I_2 and I_3 are three phase currents, then neutral current I_n calculated as,

$$I_n = I_1 + I_2 + I_3 \quad (2)$$

All the values in eq. (2) are vector quantities having both magnitude and current. Value of return current may become larger than any of the phase current for highly unbalanced loads. Under balanced load conditions

$I_1 = |I| \angle \theta_i$

$I_2 = |I| \angle \theta_i - 120^0$

$I_3 = |I| \angle \theta_i + 120^0$

And neutral current becomes

$I_n = I_1 + I_2 + I_3 = 0$

Unbalanced currents caused by unbalanced loads flowing through distribution lines causes unbalanced voltage drops and therefore system voltage in supply network also becomes unbalanced. A balanced current flowing through unbalanced phase impedances also result in unbalanced system voltages. Again unbalanced voltages follow the same relations as described for current. One of the definition for unbalance voltage is given by ratio of maximum deviation from average of the three voltages to average of the three voltages (Ciric. *et al.* 2003). Same definition may be taken for three currents described above. Average (I_{avg}) of the magnitudes of three unbalanced currents in three phases will be,

$$I_{avg} = \frac{I_1 + I_2 + I_3}{3} \quad (3)$$

Now for each phase current of the unbalanced three phase system will have some difference from I_{avg} given in eq. (4)

$$I_{diff} = \begin{bmatrix} |I_1 - I_{avg}| \\ |I_2 - I_{avg}| \\ |I_3 - I_{avg}| \end{bmatrix} \quad (4)$$

As maximum difference in any phase current is possible either above or below the average current therefore magnitude of the difference is shown in eq. (5).

Then percentage unbalance is given as

$$\% I_{Unbalance} = \frac{\max(eq.5)}{I_{avg}} * 100 \quad (5)$$

This definition of unbalanced factor is easiest way of understanding the degree of unbalance currents flowing in distribution system although it covers little information about phase and only covers magnitude of the currents. Table 1 explains the concept of unbalance factor based on definition given in eq. (5). Return current in neutral (I_n) is also given for different scenarios considered in table 1. Six different cases of unbalanced three phase currents are considered to observe the resulting deviation in neutral current and unbalance factor is given in eq. (5).

In case I, currents of 10A having power factor of unity (angle 0 for simplicity) is flowing through each phase indicating a complete balance in terms of both magnitude and angle. Percentage unbalance factor and neutral current are both zero. Magnitude unbalance is considered for next three cases from II to IV. Case II shows three different magnitudes of 10, 15 and 5 indicating an unbalance of 50% and neutral current of 8.66A. In case III, two phases are having a balance currents of 10A each and third phase carries zero current. This also results in unbalance factor of 50% but with a higher neutral current of 9.99A. Case IV shows even a worse condition where only one phase is carrying a load of 10A and other two phases are having zero current. Unbalance factor calculated for this case is 100% and neutral current is 10A. Although unbalance factor in case IV is twice that of case III but change in neutral current is negligible. These four cases indicate that percentage

unbalance factor given in eq. 5 is a good indicator of degree of unbalance.

Phase unbalance with equal magnitude of three currents are considered in cases V and VI to observe the results for unbalance factor and neutral current. As unbalance factor given in eq. 5 only considers magnitude of the current therefore a 0% unbalance factor results for both cases. It proves that unbalance factor alone cannot accurately indicate degree of unbalance. For case V, I_1 has unity power factor while I_2 and I_3 both have 0.9 lagging power factor. Neutral current for this case is calculated as 4.47A. For the last case VI, I_1, I_2 and I_3 respectively have unity, 0.9 and 0.8 lagging power factors. Neutral current in this case is 6.05A which is higher as compared to 4.47A of case V. Therefore neutral current seems better indicator for degree of unbalance in these cases. It is therefore suggested that unbalance factor and neutral current should both be analyzed for unbalance loading.

Table 1: Examples of load unbalance conditions

Case		Phase Currents			Neutral current	Unbalance factor
		I_1	I_2	I_3	I_n	% I_{unb}
					Eq. (2)	Eq. (5)
I	Mag.	10	10	10	0	0
	θ	0	-120	120	0	
II	Mag.	10	15	5	8.66	50
	θ	0	-120	120	90	
III	Mag	10	10	0	9.99	50
	θ	0	-120	120	-60	
IV	Mag.	10	0	0	10	100
	θ	0	-120	120	0	
V	Mag.	10	10	10	4.47	0
	θ	0	-94.2	145.9	-77.26	
VI	Mag.	10	10	10	6.05	0
	θ	0	-94.2	156.9	-89.36	

3. POWER LOSSES CAUSED BY UNBALANCED LOADING

Power losses caused by current (I) flowing through a resistance (R) is given by

$$P_{loss} = I^2R \quad (6)$$

In distribution system, current flowing through transformers, conductors and cables will cause power losses as given in eq. 6. These power losses are commonly known as copper losses or load dependent losses and falls in the category of technical losses. Unbalanced loading is one of the contributor for technical losses in the distribution system. Most of the residential and commercial loads are single phase being supplied by a two wire service mains from three phase four wire L.T. distribution system. If the degree of unbalance increases, then copper losses will increase.

To understand the losses caused by unbalanced loading, consider a simple three phase system. Total load of 30A is to be supplied by a three phase source over a three phase three wire system. Resistance (R) of each line conductor is assumed to be 0.1Ω. Hence total power losses in three phase conductors will be

$$P_{loss}=R*\left(I_1^2+I_2^2+I_3^2\right) \quad (7)$$

Table 2: Power losses in balanced and unbalanced systems

Case	Current (A)			Unbalance factor	Power Losses (W)
	I_1	I_2	I_3	Eq. 5	Eq. 7
I	10	10	10	0	30
II	9	10	11	10	30.2
III	5	10	15	50	35

In three phase four wire distribution system, power losses can be calculated using the resistances of line conductor and current flowing through it by eq. 6. Power losses are computed for three phases and neutral using power flow analysis. If $P_{loss(1)}$, $P_{loss(2)}$, $P_{loss(3)}$and $P_{loss(n)}$are power losses in each of the three phases and neutral conductors then total losses of the line segment P_{loss} will be sum of these four losses.

$$P_{loss}= P_{loss(1)}+P_{loss(2)}+P_{loss(3)}+P_{loss(n)} \quad (8)$$

$$P_{loss}= I_1^2R+I_2^2R+I_3^2R+I_n^2R$$

$$P_{loss}=R*\left(I_1^2+I_2^2+I_3^2+I_n^2\right) \quad (9)$$

Another approach to find out total power losses is to calculate sending end power (P_S) and receiving end power (P_R) for a line section and using relation of eq. 10 given below

$$P_{loss}= P_S- P_R \quad (10)$$

Power losses calculated using eq. 9 gives actual losses for each phase and neutral conductor. Procedure used to calculate total power losses in eq. 10 doesn't give accurate power losses of individual phase and neutral conductors, although total losses are accurately calculated.

4. POWER LOSS ANALYSIS FOR DISTRIBUTION FEEDER

Most of the 11 kV feeders in Hyderabad city supplies residential and commercial consumers (Farhana. *et al.* 2013). 11 kV Hayat is one of such feeder supplying electricity to portion of Sarfaraz colony, Al Rahim shopping center and surroundings. **Table 4.**

Table 4: 11 kV Hayat feeder; Transformer capacity

Transformers		Total Capacity (kVA)
Numbers	Capacity (kVA)	
2	25	50
2	50	100
7	100	700
2	200	4000
Total		4850

Table 5 shows comparison of power losses for each transformer with balanced and unbalanced loading and resulting reduction. Total power losses 31 transformers reduce from 288.39 kW to 230.68 kW through load balancing. Apart from this 57.5 kW loss reduction in L.T circuits, 6.3 kW reduction in power losses of H.T circuit s also observed as a result of reduction in current and

power losses of L.T circuits of the transformers. Hence simulation results show power loss reduction of 62.8 KW. For an average cost of Rs. 15 per kWh, Annual savings will be **Million Rs.= 2.68.** Therefore it is clear that power loss reduction through load balancing will result in immediate financial benefits in terms of loss reduction. Additional system capacity will be available for further loads equipment operating life will increase.

Table 5: Comparison of power losses for balanced and unbalanced loading on 11kV Hayat feeder

Transformer			Power Losses (kW)		
Sr.	kVA	% I_{Un} Eq (5)	Unbal	Bal	Diff
1	50	26.8%	1.74	1.6	0.14
2	200	24.3%	8.99	8.27	0.72
3	200	48.9%	5.16	3.64	1.52
4	200	7.5%	19.34	15.29	4.05
5	200	25.0%	17.56	13.21	4.35
6	200	32.9%	18.94	13.70	5.22
7	200	14.3%	7.99	5.57	2.42
8	200	37.9%	1.77	1.56	0.21
9	100	37.1%	4.22	3.67	0.55
10	100	25.4%	4.91	3.67	1.24
11	200	22.7%	5.94	5.01	0.93
12	100	8.8%	1.14	1.03	0.11
13	200	14.8%	12.6	10.99	1.61
14	200	28.4%	6.55	5.52	1.03
15	50	26.4%	0.93	0.77	0.16
16	200	19.5%	19.87	14.47	5.4
17	200	15.6%	12.82	10.98	1.84
18	200	9.6%	5.73	5.24	0.49
19	25	30.3%	0.71	0.61	0.1
20	25	43.3%	0.94	0.76	0.18
21	200	18.3%	16.38	13.78	2.6
22	200	38.7%	6.43	4.79	1.64
23	200	36.8%	8.2	5.13	3.07
24	200	19.9%	13.29	9.71	3.58
25	100	37.2%	5.14	4.42	0.72
26	200	14.5%	22.31	17.59	4.72
27	100	19.1%	8.39	7.53	0.86
28	100	3.4%	4.92	4.43	0.49
29	200	34.8%	3.05	2.39	0.66
30	200	11.7%	24.13	19.89	4.24
31	100	15.5%	18.3	15.95	2.35
Total			288.39	230.68	57.50

5. CONCLUSION

In this paper, one of the 11 kV feeder supplying residential and commercial consumers in Hyderabad city simulated using PSS SINCAL software to observe the contribution of unbalanced loading in power losses. Unbalanced loading on L.T network of distribution system contribute to increased technical losses but is often ignored by HESCO and other utilities in Pakistan. Different transformer circuits had different level of unbalance in loads. It is observed through simulation results that load balancing of the selected feeder reduces technical power losses of 62.8 kW accounting to an annual savings of Rs. 2.68 Million. Hence, it is concluded that energy efficiency is increased by load balancing, which is achievable by monitoring and load shifting by dedicated manpower. Smart meters at all distribution transformers will help to achieve unbalance load data for different intervals.

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