Impact of voltage unbalance on the performance of three-phase induction motor

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ABSTRACT

Availability of quality power has become an important issue for industrial utilities due to frequent performance variations in process industries. Increase in the generating capacity has not kept up pace of power demand, which results into shortage of power supply and power system network is normally subjected to varying and unequal loads across the three phases. Continuous variation of single-phase loads on the power system network leads to voltage variation and unbalance, most importantly; the three-phase voltages tend to become asymmetrical in nature. Application of asymmetrical voltages to induction motor driven systems severely affects its working performance. This paper presents the effects of voltage variation and unbalance on the performance of an induction motor driven centrifugal pump with a case study.

Keywords*: Current unbalance, efficiency, power factor, symmetrical components, three-phase induction motor, voltage unbalance*

1 INTRODUCTION

The widening power supply and demand gap is due to the increasing number of domestic, commercial and industrial loads. As power generation has not kept pace with the power demand, there has been an increasing stress towards energy management in the industrial sector as they are the major consumers. Adjustable speed drives (ASDs) are finding increasing acceptance in industrial and commercial utilities for energy saving purposes (Kennedy 2000). Increasing and varying load demand by domestic consumers have led to continuous switching of single-phase loads like computers, fluorescent lamps etc. has led to the power system network being subjected to time varying loads. This has led to a power quality problem, the harmful effects of which is quite damaging in the long run and has become one of the major concerns in recent years (Ezer *et al.* 2002) . Power quality is a combination of voltage quality and current quality and is mainly concerned with the deviations of voltage and/or current from the ideal, and is termed as a power quality disturbance (Bollen 2000). Of the various power quality events, voltage variations and unbalance seem to be the most commonly occurring power quality problem. The main contributor to the voltages becoming unbalanced at the three-phase terminals is the unequal distribution and operation of single-phase loads across the power system network (Jouanne and Banerjee 2001). This situation may also occur due to conditions within the utility premises as well. Though there may be fixed operating times within the utility premises, single-phase loads across the power system network continuously varies, usually with large hourly fluctuations, resulting in voltage variation and unbalance (Bhavaraju and Enjeti 1996).

Induction motors normally encounter a small level of voltage unbalance that exists in the system network. In the case of pump loads, as the torque developed by the motor is dependent on the supply voltage, small variation in the voltage or unbalance among the voltages results in a detrimental effect on the application involved (Donner *et al.* 2002). The continuous voltage variation and unbalance throughout the day does have a big impact on the working performance. Industrial utilities make significant amount of investment in order to achieve process efficiency, but many a times it has been found that performance variations in the process equipment are mainly due to external factors, in particular, the quality of the incoming supply. Hence considering the application involved, the knowledge of possible variation in performance due to the impact of voltage variation and unbalance is essential especially when it comes to identifying energy management opportunities. This paper shows the effects of voltage variation and unbalance on an induction motor driven centrifugal pump with a typical case study.

2 VOLTAGE VARIATIONS AND UNBALANCE

Voltage variations are random variations of voltage magnitudes, mainly due to arc furnaces loads, frequent or cyclic motor operations involving speed variations etc. Voltage unbalance is the non-equality of voltage magnitudes and /or voltage angles among the three-phases at any given point of time, mainly due to the unequal distribution of single-phase loads, asymmetry of line and transformer winding impedances, time varying operation of single-phase loads, traction loads, blown out fuses on three-phase capacitor banks, adjustable speed drives operations etc. (Jouanne and Banerjee 2001; Kim *et al.* 2005). The most important reason for voltage unbalance is a mismatch of reactive power demand between the industrial utilities and the generating stations (Bansal *et al.* 2002). Due to varying operating times of single-phase and three-phase loads, there exists definite possibility of voltage variations above and below the rated value, in both balanced and unbalanced form. Thus, voltage variation and unbalance can be classified into balanced overvoltage (BOV), balanced undervoltage (BUV), unbalanced overvoltage (UBOV) and unbalanced undervoltage (UBUV).

BOV is the condition wherein the three-phase voltages are individually and equally greater than the rated voltage value, BUV is the condition wherein the three-phase voltages are individually and equally lesser than the rated voltage value. UBOV is the condition wherein the three phase voltages are not equal to each other, in addition the positive sequence component of the voltage is greater than the rated voltage value while UBUV is the condition wherein the three phase voltages are not equal to each other, in addition the positive sequence component of the voltage is lesser than the rated voltage value. There is a very less possibility that all three-phase voltages remain constant at all times, hence the analysis carried out in this paper is limited to UBOV and UBUV cases.

Voltage unbalance has been mathematically expressed in a number of ways (Kim *et al.* 2005; Lee 1999; Wang 2001; Pillay *et al.* 2002; Faiz *et al.* 2004; Pillay and Manyage 2001). These expressions are simple and quite approximate in nature but normally gives erroneous results because there will be innumerable voltage combinations for a particular voltage unbalance factor (VUF).

Presence of asymmetry among the voltage magnitudes can be resolved using the classical Fortescue theorem (Fortescue 1918), according to which, the voltage phasors of a three-phase asymmetrical system can be resolved into a balanced system of voltage phasors, the components being positive sequence, negative sequence and zero sequence. In the case of delta-connected systems or in the absence of neutral connection, due to the non-availability of path for flow of zero sequence currents, zero sequence components can be safely neglected without causing any significant error. The voltage unbalance factor (VUF) as expressed by International Electrotechnical Commission (IEC) is

$$\%\,\mathrm{VUF} = \frac{V_N}{V_P} \,\mathrm{x}\, 100\,\% \tag{1}$$

Where, V_N and V_P are magnitudes of negative and positive sequence voltage components respectively.

Equation (1) gives a better understanding of voltage unbalance as it takes into account the resulting sequence components, but it can be seen that for a particular VUF, there are various combinations of positive and negative sequence voltages, as discussed in (Pillay *et al.* 2002; Faiz *et al.* 2004). As the line voltage phasors form a closed triangle, changes in the line voltage magnitudes leads to a change in the phase angle displacements of individual line voltages. This brings into the picture the phase angles of the positive and negative voltage sequence, thus implying that the phase angle of voltage unbalance needs to be considered during voltage unbalance analysis. Appropriately, the complex voltage unbalance factor (CVUF) can be written as

$$\mathrm{CVUF} = \frac{V_N\angle\theta_{VN}}{V_P\angle\theta_{VP}} = K_V\angle\,\theta_V \tag{2}$$

Where, $K_V = \left|\frac{V_N}{V_P}\right|$ is VUF, $\theta_V = (\theta_{VN} - \theta_{VP})$, phase angle by which V_N leads V_P. $V_P\angle\theta_{VP}$ and $V_N\angle\theta_{VN}$ are the positive sequence and negative voltages.

Presence of unbalance among the voltages leads to an unbalance among the currents as well. In a manner similar to equation (2), the complex current unbalance factor (CCUF) can be written as

$$\mathrm{CCUF} = \frac{I_N\angle\theta_{CN}}{I_P\angle\theta_{CP}} = K_C\angle\,\theta_C \tag{3}$$

Where, $K_C = \left|\frac{I_N}{I_P}\right|$ is the current unbalance factor, $\theta_C = (\theta_{CN} - \theta_{CP})$, phase angle by which I_N leads I_P. $I_P\angle\theta_{CP}$ and $I_N\angle\theta_{CN}$ are the positive sequence and negative sequence stator currents;

The CVUF has been put forward as a factor due to the clarity it provides to the VUF, hence making the use of angle θ_V, very much necessary during performance analysis (Wang 2001; Wang 2000).

3 THREE-PHASE INDUCTION MOTOR MODEL

Steady state performance of three-phase induction motors have been analysed by neglecting the core loss and friction and windage loss components, the reason being to facilitate ease of understanding and analysis (Wang 2001; Wang 2000; Kersting *et al.* 1997). While core loss was determined experimentally in (Wang 2001), core loss was ignored but friction and windage loss was considered in (Pillay *et al.* 2002). In industrial situations, the utility energy bill is dependent on components like plant power factor, total active power usage and overall efficiency of operation. It is therefore important to keep in mind that ease of analysis is not the criteria but accuracy as close as possible that should be the basis for estimation of motor parameters, especially when it comes to energy auditing and management in industrial utilities. Though it is extremely difficult to be as exact as possible but still, it is important to consider all possible quantifiable parameters during analysis. Therefore accurate estimation of losses is extremely important else there will be a significant error in the efficiency estimation (Ibiary 2003). The core loss depends on the applied voltage while friction and windage loss depends on the operating speed. The power input on no load is only to account for the no load losses in the form of stator copper loss, core loss, windage and friction loss. The steady state equivalent per phase equivalent circuit is suitably modified to take into consideration core loss and, friction and windage loss under running conditions as shown in Figure 1 (Kothari and Nagrath 2004).

In Figure 1, V is the applied voltage, R_1 and X_1 are stator resistance and reactance respectively, and rotor resistances, R'_2 and X'_2 are equivalent rotor resistance and reactance as referred to the stator, R_C is the core loss resistance, R_{FW} is the resistance representing the friction and windage loss, X_M is the magnetizing reactance, s is the operating slip, I_1 is the stator current, I_o is the no load current component and I'$_2$ is the rotor current referred to stator side. The equivalent circuit parameters of X_1, X'_2, X_M, R_C and R_{FW} can be obtained from the no load and blocked rotor tests data.

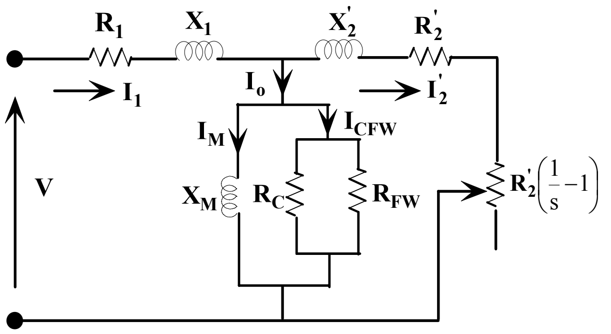

Figure 1. Per-phase equivalent circuit of induction motor

Under conditions of asymmetry, with the application of symmetrical component technique, per phase induction motor equivalent circuit can now be split up into a positive sequence equivalent circuit and negative sequence equivalent circuit. Let V_{RY}, V_{YB} and V_{BR} be the measured line-to-line voltage magnitudes, with V_{RY} being taken as the reference phasor.

For the positive sequence equivalent circuit,

$$V_P\angle\theta_{VP} = \frac{V_{RY}\angle 0 \ + \ a\,V_{YB}\angle\theta_{YB} \ + \ a^2 V_{BR}\angle\theta_{BR}}{3} \quad (4)$$

$$I_{1P}\angle\theta_{CP} = \frac{V_P\angle\theta_{VN}}{Z_P\angle\varphi_P} \quad (5)$$

For negative sequence equivalent circuit,

(6)

$$I_{1N}\angle\theta_{CN} = \frac{V_N\angle\theta_{VN}}{Z_N\angle\varphi_N} \quad (7)$$

Where, $V_P\angle\theta_{VP}$ and $V_N\angle\theta_{VN}$ are the positive sequence and negative sequence voltages; $I_{1P}\angle\theta_{CP}$ and $I_{1N}\angle\theta_{CN}$ are the positive sequence and negative sequence stator currents; $Z_P\angle\varphi_P$ and $Z_N\angle\varphi_N$ are the positive sequence and negative sequence input impedances; operator $a = 1\angle 120°$ and $a^2 = 1\angle -120°$.

Thus under voltage unbalance conditions, the induction motor can be considered as two separate motors in operation, one operating with a positive sequence voltage V_P and slip 's', and other operating with a negative sequence voltage V_N and slip ' (2 - s) ' (Wang 2001).

The individual line currents can now be written as

$$I_R\angle\theta_R = I_P\angle\theta_{CP} + I_N\angle\theta_{CN} \quad (8)$$

$$I_Y\angle\theta_Y = a^2\, I_P\angle\theta_{CP} + a\, I_N\angle\theta_{CN} \quad (9)$$

$$I_B\angle\theta_B = a\, I_P\angle\theta_{CP} + a^2\, I_N\angle\theta_{CN} \quad (10)$$

The actual power output is the sum of the power output components,

$$P_o = P_P + P_N \quad (11)$$

Positive sequence power

$$\text{output}, P_P = \frac{3\,(I'_{2P})^2 R'_2(1-s)}{s} \quad (12)$$

Negative sequence power output,

$$P_N = \frac{3\,(I'_{2N})^2 R'_2(s-1)}{(2-s)} \quad (13)$$

Where, I'_{2P} and I'_{2N} are positive and negative sequence rotor current components.

For steady state operation, $T_M = T_L$ (14)

Where, T_M is the torque developed by motor and T_L is the load torque.

Under conditions of voltage unbalance,

$$T_M = T_P + T_N \quad (15)$$

Where, T_P and T_N are the positive and negative sequence torque components

The total power input

$$P_{IN} = \text{Real}\,[3\ (V_P\, I_P^* + V_N\, I_N^*)] \quad (16)$$

Where '*' indicates the conjugate value

Motor Efficiency is given by

$$\%\,\eta = \frac{P_P + P_N}{P_{IN}} \text{x}\,100\,\% \quad (17)$$

A 3ϕ, 2 pole, 50 Hz, 1.5 kW, 415 V induction motor driving a centrifugal pump having the following equivalent circuit parameters obtained from the no load and blocked rotor tests R_1 = 4.75 Ω, $X_1 = X'_2$ = 2.63 Ω, R'_2 = 5.05 Ω, R_C = 633.21 Ω, R_{FW} = 1918.52 Ω, X_M = 118.71 Ω; is considered for analysis. Under rated balanced voltage conditions the system was found to be operating at a slip of 0.0462.

4 RESULT ANALYSIS

NEMA guidelines do not recommend operating a motor for voltage unbalance above 5% (Wang 2001). The motor set up is now subjected to voltage variation and unbalance ranging from 1% to 5**%.** To further facilitate the analysis, the following assumptions are made (a) all circuit elements are constant (b) Core loss and Friction and Windage Loss, are included as part of the equivalent circuit (c) Supply frequency is assumed to remain constant. The parameters taken up for analysis are: current unbalance, line current, magnetizing current, rotor current, total losses, and efficiency.

4.1 CURRENT UNBALANCE

Changing the applied voltage above or below the rated value changes the speed of operation. From eqn (3), (Wang 2001; Wang 2000), the current unbalance factor

$$K_C = \left|\frac{I_N}{I_P}\right| = \left|K_V \frac{Z_P}{Z_N}\right| \tag{18}$$

Under normal circumstances, positive sequence impedance Z_{1P} will be larger than the negative sequence impedance Z_{1N}; therefore, smaller magnitudes of voltage unbalance leads to a larger magnitude of unbalance among the currents, which increases at a larger rate as the voltage unbalance rate increases.

As shown in Figure 2, the rate of increase in current unbalance for UBOV case is in the range of 8.62% to 43.62% while for UBUV case, it is in the range of 8.43% to 40.35%. It can be seen that for a normally existing case of voltage unbalance rate of 1%, the current unbalance rate would be in excess of 8%, which is quite large by any means. In the example presented, the % current unbalance for UBOV case is higher than that for the UBUV case, due to the fact that magnetising current component was drawing a larger portion of line current. This unbalance among the currents will now be responsible for unequal individual phase contribution towards total losses, hence increasing the temperatures inside the motor.

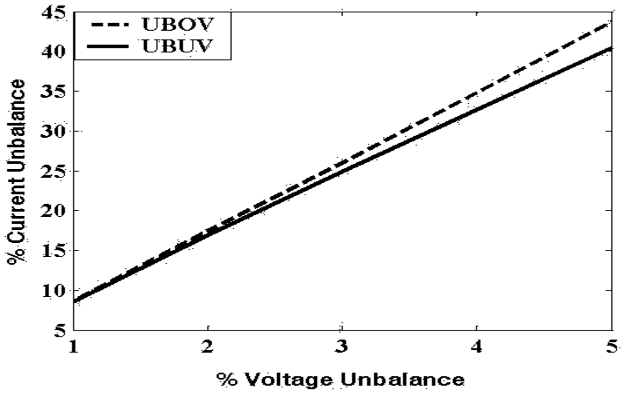

Figure 2. Current Unbalance vs Voltage Unbalance

4.2 LINE CURRENTS

For the sake of simplicity of analysis, 'R' phase is taken as reference and all % values (increase or decrease) are with respect to those under rated balanced conditions. It can be seen that due to voltage unbalance and subsequently larger current unbalance, there is a big increase in the line current magnitude of 'R', as shown in Figure 3. For the UBOV case, the reference current variation was in the range of 7.13% to 44.13% while for the UBUV case, it was 6.24% to 37.51%.

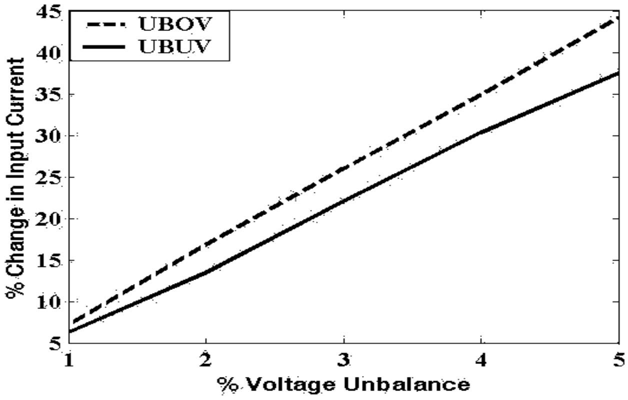

Figure 3. % Change in Input Line current

4.3 MAGNETISING CURRENT

Figure 4 shows the variation of the magnetising current under unbalance. For the UBOV case, the increase is in the range of 1.75% to 5.78% with respect to that under balanced conditions while for the UBUV case, as expected the decrease is in the range of 0.21% to 3.17%. It is evident that the rate of increase and decrease is not the same. This is because of the fact that under conditions of increasing voltage, core saturation takes place at a faster rate, thus requiring a larger magnitude to further magnetize it.

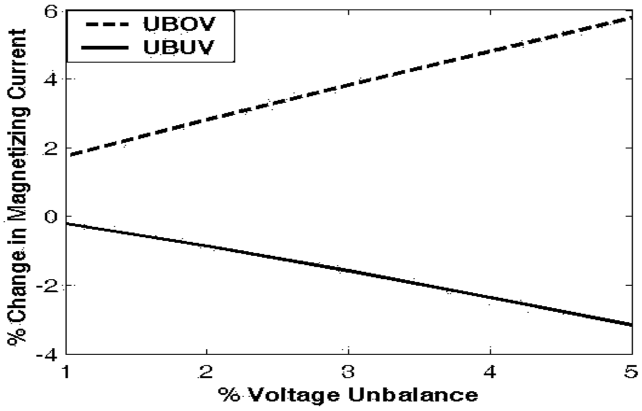

Figure 4. % Change in Magnetising Current

4.4 ROTOR CURRENT

Figure 5 shows the variation of the rotor current under unbalance voltage conditions. For the UBOV case, the increase is in the range of 11.74% to 59.09% while for the UBUV case, as expected the increase is even higher, 12.58% to 65.39%, thereby increasing its contribution towards total losses.

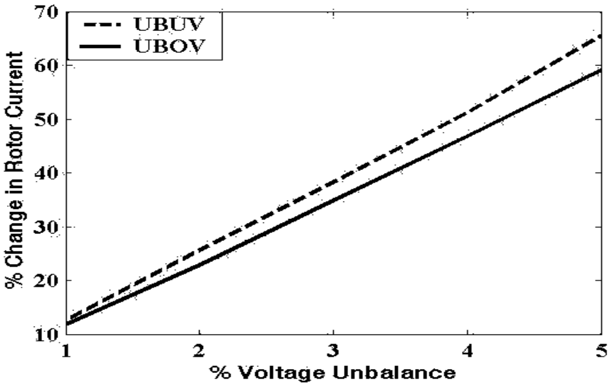

Figure 5. % Change in Rotor current

4.5 TOTAL LOSSES

Figure 6 shows the variation of total losses under unbalance. The total losses considered are stator and rotor copper losses, core loss, windage and friction loss. As shown, for the UBOV case, the increase is in the range of 8.15% to 55.69% while for the UBUV case, the increase is in the range of 7.74% to 39.39%. It was found that the magnetising current magnitude had a dominating effect over the rotor current, hence the case of UBOV losses being greater than the UBUV losses.

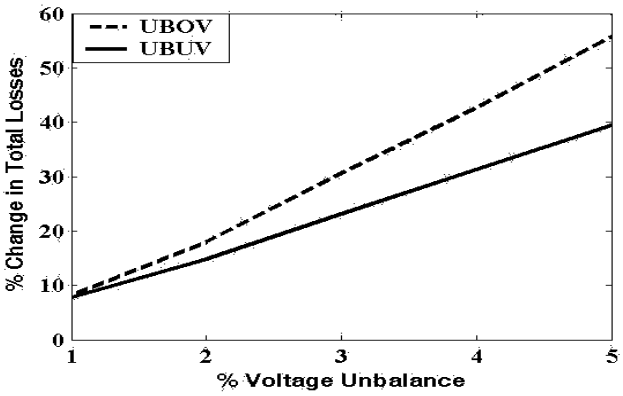

Figure 6. % Change in Total Losses

Putting all things together, it can be seen that increase in either magnetizing current or rotor current, is quite dangerous especially for stator conductors. Prolonged operation under such conditions may trigger frequent operation of safety devices in addition to unnecessary heating of stator conductors, and subsequent damage to the insulation. Also, the load delivering capacity will be severely affected in the long run, thereby shortening the motor useful life.

4.6 EFFICIENCY

Efficiency of motor plays an important role in the power bill of an industrial utility. Almost all industrial utilities make use of motor driven systems in one form or the other. An industrial customer will always have long and sometimes continuous working hours. Plant efficiency is usually the reference index for the determining the plant performance and estimating the energy charges. Higher value of efficiency means lesser energy charges for same work done. As shown in Figure 7, for the UBUV case, the efficiency decrease is in the range of 0.04% to 1.64% while for the UBOV case, it is 0.45% to 3.57%. For a small amounts of unbalance that always exists in the system, as shown, the decrease in efficiency is negligibly small, but as already covered in the preceding discussions with respect to current unbalance and line current variations, larger magnitudes of unbalance does have detrimental effects on the motor.

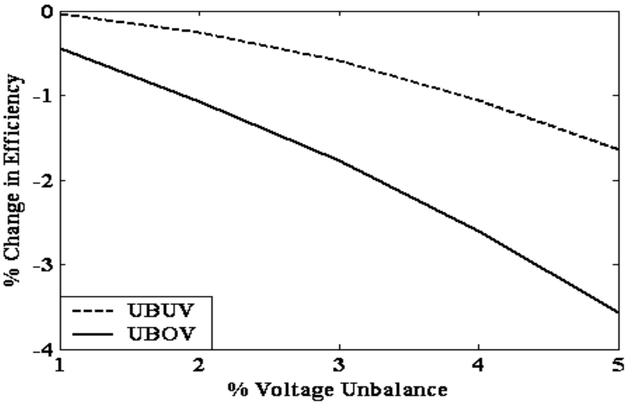

Figure 7. % Change in Efficiency

The importance of accuracy with respect to estimating the motor efficiency can be understood by estimating the motor efficiency by (a) totally ignoring the core loss and friction and windage loss (b) considering core loss and friction and windage loss.

When we totally ignore the core loss and friction and windage loss, for UBOV case, the % deviation in efficiency estimation was in the decreasing range of 23.99% to 23.92%, while for the UBUV case the decreasing range was 23.04% to 20.81%. When we assume constant core loss and friction and windage loss, for UBOV case, the % deviation in efficiency estimation was in the increasing range of 2.83% to 3.83%, while for the UBUV case the decreasing range was 1.47% to 0.16%. To put in another way, totally neglecting the core loss and friction and windage loss results in estimating the efficiency to be actually higher than the actual accurate value i.e.; for 1% UBOV case, efficiency of the motor would be estimated to be 23.99% more than the efficiency at 1% UBOV with core loss and friction loss taken into account. The above numbers only highlights the fact that losses that are quantifiable in nature should never be neglected nor assumed to be constant for simplicity purposes. This is extremely important as efficiency and losses never remain the same over the working life of the subjected to various supply and load conditions. Hence it should be concluded that for industrial situations where there is accountability in every sense of the word, it is accuracy and not simplicity; that should be the criteria for performance review and subsequent result analysis.

5 CONCLUSIONS

A performance analysis of a three-phase induction motor driving a centrifugal pump is carried out for voltage variation and unbalance ranging from 1% to 5% for UBOV and UBUV cases. The complex nature of voltage unbalance factor is taken into account to analyze the effect of voltage variation and unbalance using the symmetrical component technique. Core loss, windage and friction loss which have been neglected in previous research works, has been considered in present work for better accuracy of results and it has been shown that its neglect does lead to wrong estimation of operating efficiencies, subsequently wrong result analysis.

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