Power losses evaluation in low voltage distribution network: a case study of 250 kVA, 11/0.416 kV substation

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Article Info

Article history:

Received Apr 9, 2021
Revised Oct 27, 2021
Accepted Nov 18, 2021

Keywords:

Low voltage
Network balancing
Power loss
Unbalance load
Unequal load distribution

ABSTRACT

Nowadays, the electrical system is more complicated duet to the continuous growing. Power losses is the biggest challenges for distribution network operators. There are several causes for technical losses. Losses caused by unbalanced phase current are one of the main reasons which can be minimized by small investment through dedicating a technical line staff. As a result of connecting many single loads to three phase four wire power supplies, the current flowing in each phase will be unequal and accordingly there will be a current flowing in the neutral wire. Unbalancing currents in phases can lead to increase the conductor temperature and accordingly the conductor resistance is higher which contribute to increase the power losses. Loss reduction can lead to enormous utility saving. Besides, it increases system capacity and save more money which can be used later for future planted system. This study concentrated on the amount of copper losses in distribution networks as a result of unequal loading of the three phases four wires network. The distribution network is more efficient and more economic assuming that the right procedure is applied to balance the distribution system and achieve the required calculations which require a little investment.

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1. INTRODUCTION

Electrical power is generated at power stations, then transmitted by transmission lines and finally distributed through the distribution system. The electricity injected into the distribution network is not totally paid for by the consumer. The difference between the amount of electricity entered the distribution and that is received is called distribution losses. The system disturbance may work with voltage balance/symmetrical or unbalance/asymmetrical. Besides, distribution losses are classified into technical and non-technical losses [1], [2]. Technical losses represent the power dissipated in distribution transformers, distribution lines and metering devices while the non-technical losses are result of external factors such as theft of electricity, non-payment bills by consumers and errors in reading the energy meters and keeping data. In any generation and distribution system, there is no ideal efficiency, which means there is no electrical power supplied and totally consumed by consumers without any power waste or loss. Therefore, as long as electrical power flow in any power distribution components, a certain amount of the power are lost between the generation station and load points [3]. There are several factors that contribute to increase the technical losses in distribution sector such as the quality of the conductors, length of the lines, type of the connected loads and the unbalance in phase loading.

Also, most loads are home and industrial loads type, which are inductive in nature with lag power factor and this cause power losses in the distribution power system [4]. Power electronics switching devices will increase also power loss and complexity [5]. The efficiency of the distribution power system compares the power injected into distribution system with the power received by the consumers. Therefore, the losses reduce the system efficiency as the power at receiving end is always less than the sending power.

Several methods have been addressed by researchers to study the effect of unbalanced loads on the power system losses [6]. In work [7], [8], the researchers examined how a distribution transformer is influenced by copper losses. The effect of both balanced and unbalanced load conditions on distribution transformer are presented. The results demonstrate a much higher copper losses in distribution network in unbalanced conditions compared to balanced conditions and network reconfiguration is recommended. In [9], a mathematical model of a transformer in time domain to investigate the effect of balanced and unbalanced loads on transformer losses was proposed. The transformer losses depending on the degree of the load asymmetry is proved. An additional power loss in the transformer is reduced by 48% with using load balancing unit. In [10], a radial distribution network in simulated using OpenDSS software platform to study the effect on imbalanced load on the quality and efficiency of the distribution network. It has been considered a significant step toward decreasing the existing unbalanced condition. Another research is conducted in [11] and targeted to outline the requirements for balancing three phase installation in many countries. It found that the phase balancing standard is only available in Japan. The study [12] shows a very large number of unbalanced feeders in the UK, Europe, US and China. It mentions that in the Cardiff city of the UK, the current of heaviest phase is 50% higher the current in lightest phase. The unbalance in phase have several negative consequences such as increasing transformer and network losses, nuisance tripping of protection devices and network expansion is required because the network asset is unable to take their real capacity [12]. The technique for balancing the phases of low voltage distribution network can be conducted in both design and operation stages to reduce losses in distribution network and transformer. Usually, it is difficult to have an optimum balanced network despite the proper design and operation due to the changes in the load and network expansion [9], [10]. Consequently, some phases will be heavily loaded while others will be lightly loaded which will result in current flowing in the neutral [13]. In this study, power losses that affect the efficiency of the distribution network are calculated and compared in both balanced and unbalanced scenarios. The suggested system diagram is shown in Figure 1.

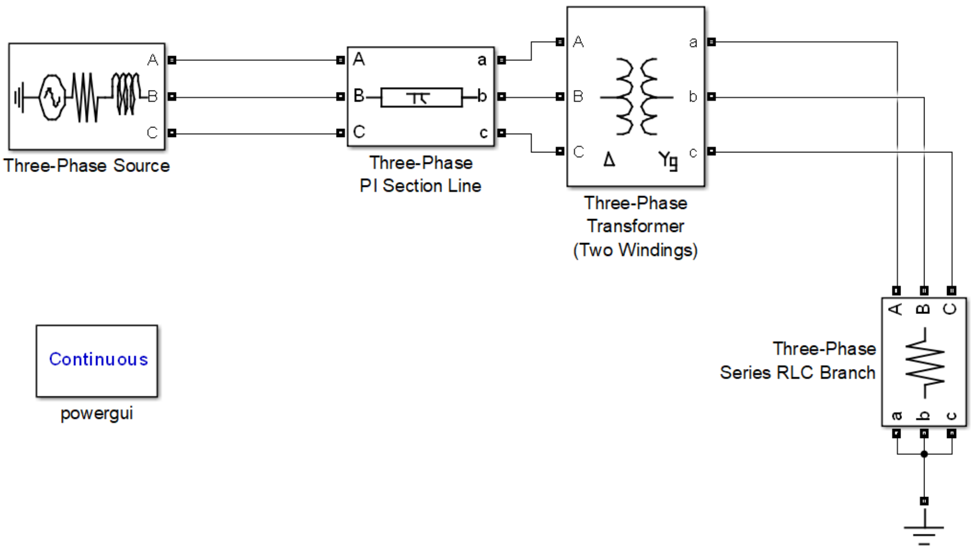

Figure 1. Simple distribution transformer network

2. LOSSES IN DISTRIBUTION IN TRANSFORMERS

Most of the transformer losses are ohmic losses. The transformer ohmic losses can be evaluated in both balanced and unbalanced conditions. Almost 30% of the total distribution and transmission losses are belong to distribution transformer losses [14]. Besides, the presence of unbalanced current can lead to reduce the service capacity of the conductors and transformers [15], [16]. In order to examine the impact of unbalanced loads on distribution transformers, the following case study is considered.

Case study:

The vast majority of the distribution transformers in Duhok electricity network are pole mounted transformer. Duhok distribution network consists of different sizes of distribution 11/0.416 kV transformers including 50 kVA, 100 kVA, 250 kVA, 400 kVA, 630 kVA, 1000 kVA, 1250 kVA, 1600 kVA, 2000 kVA and 2500 kVA [17]. The majority of these transformers are of 250 kVA capacity. The full current of a 250 kVA, 11/0.416 kV transformer is calculated as per (1):

$$S = \sqrt{3} * V_L * I_L \quad (1)$$

where S is the apparent power of transformer (VA), V_L is line voltage in volt, I_L is the line current in ampere. The total copper losses (P_{loss}) under balanced transformer feeder network condition are calculated by (2) [8], [18]:

$$P_{loss} = 3I^2R \quad (2)$$

where I is the transformer phase current and R is the transformer winding resistance. The total copper losses of the transformer in the unbalanced load condition can be calculated using (3) [7], [19]:

$$P_{loss} = R(I_R^2 + I_Y^2 + I_B^2) \quad (3)$$

where I_R, I_Y, I_B are red, yellow, blue phase currents respectively. If I_1, R_1, I_2, R_2 represent the primary and secondary currents and resistances respectively. The values of R_1, R_2 are 5.2123Ω and 0.002771Ω respectively [20]. The primary side of the transformer is connected in delta connection, then R_1 is multiplied by 1.5 and equal to 7.8185Ω [21], [22]. The measured resistance $R_{1,2m}$ can be converted to standard temperature of 75 °C as per (4) [21]:

$$R_{m(1,2)} = R_{1,2}\frac{T_{75}+235}{T_{am}+235} \quad (4)$$

where T_{75} is the standard temperature of 75 °C and T_{am} is the ambient temperature and equal to 25.7 °C [20]. Applying (4), R_1=9.3Ω and R_2=0.0033Ω.

Assuming the phase current readings for the secondary side of 250 kVA, 11/0.416 kV transformer are I_R=300 A, I_Y=250 A, I_B=200 A. The unbalanced current percentage can be obtained as (5) [11], [23]-[25].

$$I_u = \frac{I_d}{I_a} * 100\% \quad (5)$$

where I_u is the unbalanced current percentage I_d is the maximum deviation current from the average, I_a is the average value of the three-phase current.

$$I_u = \frac{50}{250} \times 100\% = 20\%$$

For ideal transformer [26],

$$V_1I_1 = V_2I_2 \quad (6)$$

where V_1, I_1, V_2, I_2 are voltage and current of primary and secondary side of the transformer, respectively.

$$V_1 = 11000v \& V_2 = 416v$$

Applying (6), the currents in primary side of the transformer are: $I_R = 11.345\ A, I_Y = 9.46\ A, I_B = 7.56\ A$.

The formula for the total copper losses in both sides of the transformer is (7) [27], [28]:

$$P_{loss} = I_1^2R_1 + I_2^2R_2 \quad (7)$$

Copper losses for primary of transformer = $(11.345^2 + 9.46^2 + 7.56^2) \times 9.3 = 2561$ W. Copper losses for secondary of transformer $(300^2 + 250^2 + 200^2) \times 0.0033 = 635.25$ W. So, the total copper losses in the transformer under unbalanced conditions = $2561 + 635.25 = 3196.25\ W$.

If the above loads are equally distributed between transformer phases, the losses will decrease as shown:

Copper losses for primary of transformer $= 3 \times 9.462 \times 9.3 = 2496.8\ W$. Copper losses for secondary of transformer $= 3 \times 2502 \times 0.0033 = 618.25\ W$. So the total copper losses in the transformer under balanced conditions $= 2496.8 + 618.75 = 3115.5\ W$. The copper losses caused by unbalanced loads on transformer are determined by (8) [7].

$$P_{loss} = ((I_R^2 + I_Y^2 + I_B^2) - 3I_n^2)R \quad (8)$$

Transformer losses due to unbalanced level of 20% $= 3196.25 - 3115.5 = 80.75\ W$. Table 1 shows different scenarios for the transformer phase currents and the corresponding copper losses for each scenario. From Table 1, it is clear that the more severe is the difference between phase currents, the higher the unbalanced percentages which consequently leads to significant increase in power losses. Figure 2 explains how the transformer copper losses are increased with an increase in unbalanced percentages caused by unevenly loading of the phase currents.

Table 1. Copper losses versus phase currents

#	I_R (A)	I_Y (A)	I_B (A)	Losses due to unbalanced conditions (W)
1	280	270	250	7.75
2	280	280	240	10
3	290	280	230	17.71
4	285	295	220	34.31
5	295	290	215	55.06
6	280	310	210	87.43
7	330	275	205	130.32

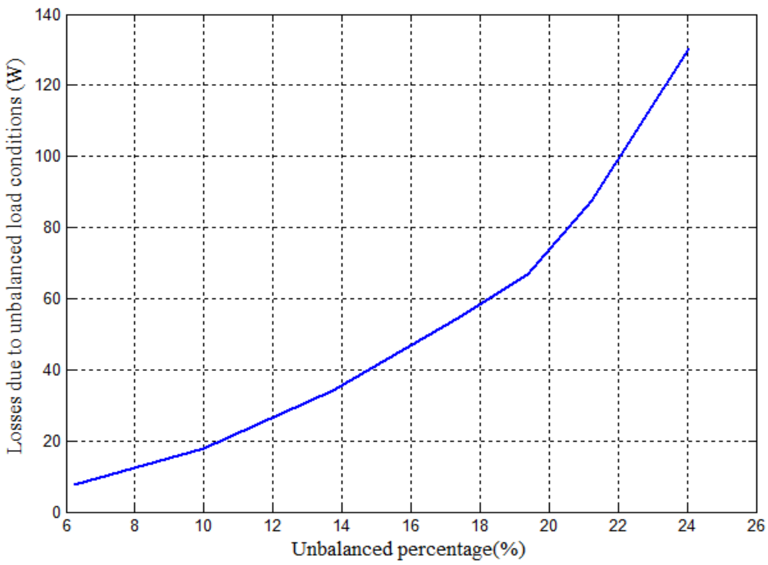

Figure 2. Relationship between transformer copper losses and unbalanced percentages

3. LOSSES CAUSED BY UNBALANCED LOADING OF DISTRIBUTION NETWORKS

The term power losses usually refer to power losses in the conductors which are commonly known as copper or ohmic losses. These losses are classified under technical losses category. To study and compare the conductor losses under balanced and unbalanced conditions, the below cases are considered and well addressed.

3.1. Case 1

Assume the load of 750 A is supplied by three phase-four wire source at the distance of 200m. The load is evenly distributed over three-phase and no current is flowing in the neutral. The conductor type is all aluminum conductor (AAC) 95 mm^2 with direct current (DC) resistance of 0.3081 Ω/km at 20 °C [29]. The effect of current flowing in the conductor at actual temperature of the conductor can be determined by (9) [23]:

$$t_1 = t_a + \frac{(3*I_b+I_n)^2}{(3*I_t)^2}(t_p - t_r) \quad (9)$$

where I_b is phase current, I_n is the neutral current, t_a is the ambient temperature, t_p is maximum conductor temperature limit and equal to 93 °C [17], t_r is reference temperature and equal to 20 °C [9], I_t is current carrying capacity for the conductor and equal to 335 A [29]. The symbols t_a, t_p, t_r are ambient temperature, maximum conductor temperature limit (93 °C) and reference ambient temperature [9]. The current carrying capacity for AAC 95 mm^2 is 335 A [29]. Flowing current in the conductor increases the conductor heating and consequently the conductor resistance is higher [30]. Conductor temperature has a linear relation with DC conductor resistance which is (10) [31], [32]:

$$R = R_{20}[1 + \alpha_{20}(T - 20)] \quad (10)$$

R_{20} is the resistance of the conductor at temperature of 20 °C, and α_{20} is the temperature coefficient of conductor and equal to 0.00391 at 20 °C [31]. At ambient temperature of 35 °C and based on (8) and (9), the actual resistance of the conductor can be obtained as:

$$t_1 = 35 + \frac{(3 \times 250 + 0)^2}{(3 \times 335)^2}(93 - 20) = 75.65\,°C$$

Corresponding DC resistance is,

$$R = 0.3081[1 + 0.00391(75.65 - 20)] = 0.3753 \Omega/km$$

The total ohmic losses under balanced transformer conditions are calculated using (10) [26].

$$P_{loss} = 3 \times I^2 \times R \times L \quad (11)$$

I is the current in circuit (A), R is the resistance of the conductor ((Ω / km) , L is conductor length (km).

$$P_{loss} = 3 \times 250^2 \times 0.3753 \times 0.2 = 14.07 \text{ kW}$$

3.2. Case 2

Assume the load of 750 A is supplied by three phase-four wire source at the distance of 200 m. The load is unequally distributed over three phases as, $I_R = 265$ A, $I_Y = 275$ A, $I_B = 210$ A, and $I_n = 65$ A. In the presence of unbalanced loads, the current will pass through the neutral and will create the power losses based on the (12) [24],

$$P_{loss(N)} = I_N^2 \times R_N \quad (12)$$

$$t_1 = 35 + \frac{(265 + 275 + 210 + 65)^2}{(3x335)^2}(93 - 20) = 83\text{ °C}$$

For simplicity of calculations and comparison with previous case, it has been assumed that $R_{AC}=R_{DC}= R$. The conductor resistance (R) at 83 °C conductor operating temperature is:

$$R = 0.3081[1 + 0.00391(83 - 20\text{ °C})] = 0.3834\ \Omega/\text{km}$$

The total copper losses under unbalanced conditions are determined using (11) [25], [26], [33].

$$P_{loss} = (3 \times I^2 + I_n^2)xR \times L \quad (13)$$

$$P_{loss} = (265^2 + 275^2 + 210^2 + 65^2) \times 0.3834 \times 0.2 = 14.89\ kW$$

The unbalanced current percentage for case study 2 according to (5) is:

$$I_u = \frac{25}{250} * 100\% = 10\%$$

The copper losses due to 10% unbalanced condition $= P_{unbalanced} - P_{balanced} = 14.89 - 14.07 = 0.82$ kW. In case 1, the network is considered to be balanced while the unbalanced percentage in case 2 reached 10%. By comparing the amount of power losses in both cases, it is obvious that copper losses are increased due to the unbalanced current in phases and following the current in the neutral.

4. CONCLUSION

In this paper, the distribution network losses and transformer losses under balanced and unbalanced conditions are examined. Different scenarios for unbalanced percentages are addressed and the losses for both the distribution network and transformers are compared. It is clear that the losses are significantly increased with an increase in the unbalanced percentages. For instance, unbalanced percentage of 10% in distribution network, caused 820 watts as a copper losses. Therefore, it is recommended that the electricity distribution owners should pay more attention to reducing the power losses by minimizing the unbalanced percentages which require a little investment in distribution sector.

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