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STUDY OF IMPACT OF VOLTAGE UNBALANCE AND PROTECTION AGAINST VOLTAGE UNBALANCE IN 3-PHASE INDUCTION MOTOR

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Abstract—
This paper provides the effect of unbalance supply condition on the performance of three-phase induction motor. It also provides the protection aspect of motor against the said unbalanced supply voltage. The loss of lifetime due to the unbalance supply condition of induction motor has been discussed in this work. Different type of voltage unbalance has been discussed along with the simulation results.

Keywords— Voltage unbalance, Induction motor, protection, 3-phase induction motor

I. INTRODUCTION

Three-phase induction motors are one of the widely used motor in different industry which operate below synchronous speed while in motoring operation and above the synchronous speed while in generating condition. In ideal condition, the 3-phase supply voltage of the induction motor is balanced in nature but in practice, unbalanced supply can be encountered. Due to the unbalanced supply voltage, the performance and efficiency of the motor deteriorates to a larger degree. The extent of deterioration of performance need to be ascertained when there is an unbalanced supply.
The assessment of unbalanced voltage has been discussed in [1]. A review of assessment of performance of induction motor during unbalance supply voltage has been discussed in [2,3]. The loss of life of induction motor due to operating in unbalanced supply voltage has been discussed in [4]. The effect of the voltage unbalance condition on performance of induction motor has been discussed in [5]. Protection against voltage unbalance condition on the induction motor has been discussed in [6]. A comparative analysis of different protection mechanism for different class of motors has been presented in [7]. The impact of unbalance in voltage and frequency on performance of single and cascaded induction motor has been detailed in [8].
This paper provides the mathematical modelling of 3-phase induction motor and the effect of unbalanced supply voltage on the performance of induction motor. This work also emphasis on the different protection devices used for mitigating the adverse effect of unbalanced supply voltage on the performance of induction motor.
This paper is organized as follows. Section II provides the mathematical modelling of induction motor, Section III provides the definition of unbalanced supply voltage and different protection mechanism for unbalanced supply condition. Section IV provides the simulation results and Section V provides the concluding remarks.

II. INDUCTION MOTOR: MATHEMATICAL MODELLING

The phase voltage of stator for 3-phase induction motor can be represented as

$$U_{sa} = R_{sa} i_{sa} + \frac{d\Psi_{sa}}{dt}$$
$$U_{sb} = R_{sb} i_{sb} + \frac{d\Psi_{sb}}{dt}$$
$$U_{sc} = R_{sc} i_{sc} + \frac{d\Psi_{sc}}{dt} \quad (1)$$

The phase voltage of rotor for 3-phase induction motor can be represented as

$$U_{ra} = R_{ra} i_{ra} + \frac{d\Psi_{ra}}{dt}$$
$$U_{rb} = R_{rb} i_{rb} + \frac{d\Psi_{rb}}{dt}$$
$$U_{rc} = R_{rc} i_{rc} + \frac{d\Psi_{rc}}{dt} \quad (2)$$

Where is the flux linkage of stator, is the flux linkage of rotor, is the rotor resistance, is the stator resistance, and are stator and rotor voltage respectively. and are stator and rotor current respectively.

$$\Psi_{sa} = L_s i_{sa} + l_{sr}\left[i_{ra}\cos(x) + i_{rb}\cos\left(x+\frac{2\pi}{3}\right) + i_{rc}\cos\left(x+\frac{2\pi}{3}\right)\right]$$
$$\Psi_{sb} = L_s i_{sb} + l_{sr}\left[i_{ra}\cos\left(x+\frac{4\pi}{3}\right) + i_{rb}\cos(x) + i_{rc}\cos\left(x+\frac{2\pi}{3}\right)\right]$$
$$\Psi_{sc} = L_s i_{sc} + l_{sr}\left[i_{ra}\cos\left(x+\frac{2\pi}{3}\right) + i_{rb}\cos\left(x+\frac{4\pi}{3}\right) + i_{rc}\cos(x)\right] \quad (3)$$
$$\Psi_{ra} = L_r i_{ra} + l_{sr}\left[i_{sa}\cos(x) + i_{sb}\cos\left(-x+\frac{2\pi}{3}\right) + i_{sc}\cos\left(-x+\frac{4\pi}{3}\right)\right]$$
$$\Psi_{rb} = L_r i_{rb} + l_{sr}\left[i_{sa}\cos\left(-x+\frac{4\pi}{3}\right) + i_{sb}\cos(x) + i_{sc}\cos\left(-x+\frac{2\pi}{3}\right)\right]$$
$$\Psi_{rc} = L_r i_{rc} + l_{sr}\left[i_{sa}\cos\left(x+\frac{2\pi}{3}\right) + i_{sb}\cos\left(x+\frac{4\pi}{3}\right) + i_{sc}\cos(x)\right]$$

$$l_{sr} = \frac{2}{3} L_m \quad (4)$$

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L_m is the mutual inductance $L_r = L_{1r} + L_m$ $J\frac{d\omega_m}{dt} = T_e - f\omega_m - T_m$

$$U_q = \frac{2}{3}\left[U_a \cos\theta + U_b \cos\left(\theta - \frac{2\pi}{3}\right) + U_c \cos\left(\theta + \frac{2\pi}{3}\right)\right]$$
$$U_d = \frac{2}{3}\left[U_a \sin\theta + U_b \sin\left(\theta - \frac{2\pi}{3}\right) + U_c \sin\left(\theta + \frac{2\pi}{3}\right)\right] \quad (5)$$

III. VOLTAGE UNBALANCE CONDITION AND PROTECTION IN INDUCTION MOTOR

$$\overline{VUF} = VUF\angle\alpha_u$$

Voltage unbalance (VU) is defined in IEEE, IEC and NEMA standards which can be represented as According to NEMA, Line voltage unbalance ratio (LVUR) can be represented as

$$LVUR = \frac{\max\left(\left|V_{ab} - V_{avg}\right|, \left|V_{bc} - V_{avg}\right|, \left|V_{ca} - V_{avg}\right|\right)}{V_{avg}}$$

$$V_{avg} = \frac{1}{3}\left(V_{ab} + V_{bc} + V_{ca}\right)$$

In NEMA definition of LVUR, phase angle are not included.
According to IEEE definition, Phase voltage unbalance ratio (PVUR) can be represented as

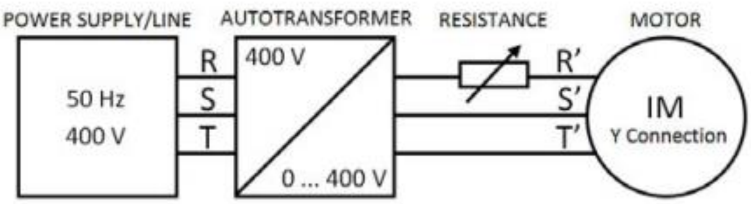
$$PVUR = \frac{\max\left(\left|V_{ph\_a} - V_{avg}\right|, \left|V_{ph\_b} - V_{avg}\right|, \left|V_{ph\_c} - V_{avg}\right|\right)}{V_{avg}}$$

$$V_{avg} = \frac{1}{3}\left(V_{ab} + V_{bc} + V_{ca}\right)$$

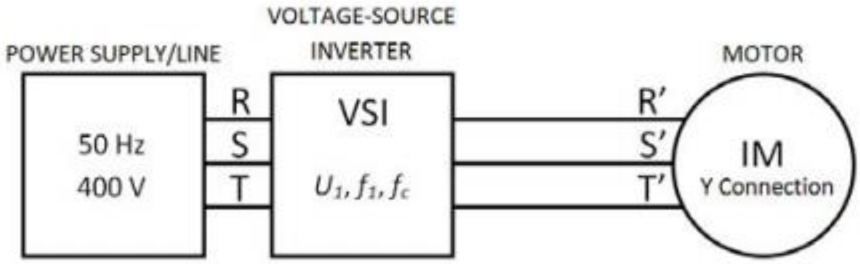
In IEEE definition also, the phase angle is not considered.
The true definition of %VUF is the ratio between negative sequence of voltage component to positive sequence of voltage component.

$$V_p = \frac{V_{ab} + aV_{bc} + a^2V_{ca}}{3}$$
$$V_n = \frac{V_{ab} + a^2V_{bc} + aV_{ca}}{3}$$
$$a = 1\angle 120^\circ$$
$$a^2 = 1\angle 240^\circ$$

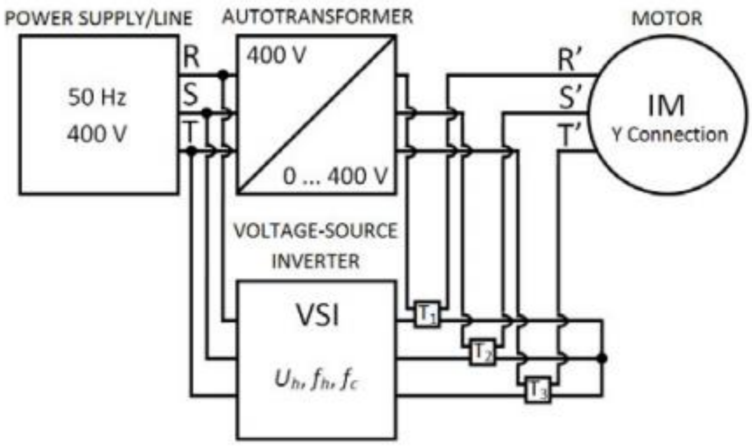
Figure 1(a) provides the connection of Y connected induction motor using 400V 3-phase supply and auto-transformer. Figure 1(b) provides the connection of Y-connected induction motor using voltage source inverter whereas Figure 1(c) provides the test setup which includes both auto transformer as well as inverter for connection of supply voltage to the inverter. This test setup is used to evaluate the individual harmonics.



(a)



(b)



(c)

Figure 1: (a,b) Test step-up to evaluate the effect of unbalanced supply condition on induction motor, (c) Test setup to evaluate the effect of unbalanced supply condition on induction motor and individual harmonics

A. Protection Against Voltage Unbalance

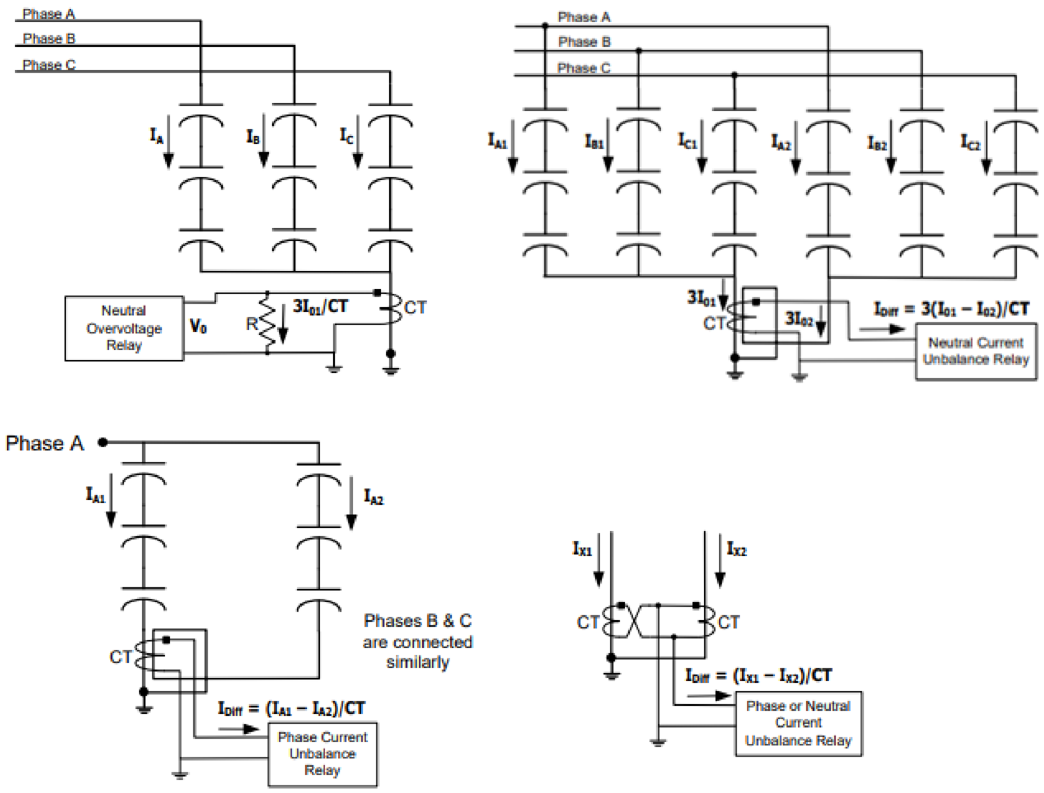


Figure 2: (a) Single-phase capacitor bank with neutral overvoltage relay, (b) 3-phase capacitor bank with neutral overvoltage relay, (c) Multiple capacitor bank in single-phase with phase current unbalance relay, (d) phase current unbalance relay

Figure 2 provides the protection circuit which acts against the voltage unbalance condition which uses neutral overvoltage relay and neural current unbalance relay.

IV. SIMULATION RESULTS

There are different types of voltage unbalance conditions such as

1. Three-phase under voltage unbalance (3-UV)
2. Two-phase under voltage unbalance (2-UV)
3. Single-phase under voltage unbalance
4. Single phase over voltage unbalance
5. Two-phase over voltage unbalance
6. Three phase over voltage unbalance

Table I: Analysis of voltage unbalance condition

Volt Unbalance	LVUR	PVUR	VUF	Va	Vb	Vc	Vp	Vn
Balanced	0	0	0	338.846	$338.846\angle 120^{\circ}$	$338.846\angle 120^{\circ}$	338.846	0
1ϕ OV	4.01	7.95	4	380	$338.846\angle -120^{\circ}$	$338.846\angle 120^{\circ}$	352.879	14.033
2ϕ OV	4.02	7.97	4	390	$354.715\angle -120^{\circ}$	$338.846\angle 120^{\circ}$	361.18	14.47
3ϕ OV	4.03	8	4	395	$360\angle -120^{\circ}$	$342\angle 120^{\circ}$	365.74	14.63
1ϕ UV	3.982	8.05	4	300	$338.846\angle -120^{\circ}$	$338.846\angle 120^{\circ}$	325.735	13.111
2ϕ UV	3.973	8.025	4	294	$326.117\angle -120^{\circ}$	$338.846\angle 120^{\circ}$	319.654	12.827
3ϕ UV	3.962	8	4	290	$320\angle -120^{\circ}$	$335.652\angle 120^{\circ}$	315.217	12.609

Table I provides the numerical values for a 3-phase connectivity of induction motor and different voltage unbalance metrices for different type of voltage unbalance condition.

V. CONCLUSIONS

This paper provides mathematical modelling of the 3-phase induction motor, voltage unbalance supply condition of induction motor. Different international standards for voltage unbalance have been discussed and protection circuit against the voltage unbalance has been discussed in this work. Different relay configuration for voltage unbalance has been discussed. Numerical simulation results have been provided for simulation results of different type of voltage unbalance condition.

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