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# Limitations of Steady-State Unbalanced Load Flow Software for Analysis of Induction Motor Behavior During Voltage Unbalance Conditions

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## SUMMARY

With increasing levels of penetration of distributed energy resources (DER), an increased focus has been seen in recent years on the assessment of the adequacy of distribution circuits. Three-phase distribution circuits have typically operated with high levels of unbalance, which can be caused by uneven distribution of and continuously varying nature of single-phase loads, asymmetrical three-phase capacitor bank operation due to a blown fuse, and open phase conditions. Increasing levels of intermittent DER further add to the levels of unbalance. For large industrial facilities which operate from unbalanced three-phase distribution circuits, these unbalances can become problematic.

Historically, phasor-domain unbalanced steady-state load flow software has been used to model distribution systems. Due to limitations in computing power, as well as insufficient modelling data, these programs rely on a number of assumptions. This paper will evaluate the adequacy of this simplified modeling approach with respect to motor load modeling.

The results from the simulations demonstrate the need for accurate modeling of induction motor behavior during voltage unbalance conditions.

## KEYWORDS

Distribution System Modeling, Induction Machine Modeling, Open Phase Condition, Voltage Unbalance, Power Quality

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## INTRODUCTION

Three-phase power system voltages at the point of utilization can experience different levels of voltage unbalance. Voltage unbalance in a three-phase system occurs when the phase voltage magnitudes and/or phase angles differ from balanced conditions [1]. A main source of voltage unbalance is the uneven distribution of and continuously varying nature of single-phase loads [2]. Other sources of unbalanced voltages include asymmetrical three-phase capacitor bank operation due to a blown fuse and open phase conditions (OPC) that can remain on the system for many seconds or even minutes if undetected. Unbalanced voltages are considered a power quality issue and the voltage unbalance percentage is defined in the National Electric Manufacturers Association (NEMA) Standards Publication No. MG 1-1993 [3] as the maximum deviation from average over the average of three phase-to-phase voltages. Another measure of the degree of voltage unbalance, $V_{unbalance}$, is defined as [2,4],

$$V_{unbalance}\% = \frac{V_2}{V_1} \times 100 \quad (1)$$

Where V2 is the negative sequence voltage magnitude and V1 is the positive sequence voltage magnitude. This measure of voltage unbalance will be used in the paper to indicate the degree of unbalance in the system.

The effects of voltage unbalance can have severe impacts on industrial loads such as induction motors. These effects have been extensively documented [4] and include induction motor impacts such as loss of motor life, reduction in efficiency, and motor failure [5,6]. Large industrial motor failures create enormous financial losses in production down time, equipment and material replacement costs.

Voltage unbalance, resulting in negative sequence voltage components at the motor terminals, produces a flux in the motor air gap which opposes the direction of rotation [8], creating additional braking torque, potentially causing motor stalling. Additionally, current is induced in the rotor conductors with nearly double the synchronous frequency [9]. Due to skin effect in the rotor conductors, the rotor heating is increased significantly and can lead to reduction in motor life. In the case of severe unbalances, rotor heating can result in deformation of rotor bars and lead to catastrophic mechanical failure. Based on [3], a derating factor is recommended for unbalances ranging from 1% to 5%, and operation with greater than 5% unbalance is not recommended.

A description of the negative sequence components present in induction motors during voltage unbalance is described in [6,7]. It is important that induction motor operation be studied in systems that require reliable motor operation during voltage unbalance conditions.

A complete modelling approach for power systems under general (unbalanced) conditions was developed in detail in [10]. However, due to lack of computing power, as well as due to insufficient availability of modelling data, direct modelling of distribution systems based on these techniques has, historically, been impractical. Simplified techniques based on assumptions have been developed, and generally gained acceptance for use in unbalanced load flow software for modelling of distribution systems [11]. However, these simplified techniques have limitations, and become inaccurate under some conditions. A number of unbalanced distribution system test cases have been developed in [12-15]. This paper expands on the concepts developed in those references by quantifying the modelling error over an arbitrary range of unbalances.

When modelling unbalanced three-phase distribution systems which contain large induction motors, such as large industrial facilities, the modelling software used should be able to accurately predict motor currents and motor stalling behavior. In lieu of the complete model utilized in EMT-type software, unbalanced load flow programs use a simplified, phasor-domain approach, typically consisting of a constant power demand. More advanced software will use a combination of constant impedance, constant current, and constant power, commonly referred to as the ZIP model [16]. In some cases, a heuristic algorithm has been utilized by attempting to predict motor stalling behavior, so that a constant power device is used under the conditions where the motor is believed to be running, and transitioning to a constant impedance device under conditions where the motor is believed to have stalled. The goal of this paper is to evaluate the accuracy of the simplified approach modelling software.

## METHODOLOGY

An induction motor load operating under voltage unbalance conditions is modeled in a commercial steady-state unbalanced load flow software package and in a commercial EMT-type software package. The voltage unbalance is varied over a wide range of possible operating conditions. Plots of the motor phase current magnitudes, as the voltage unbalance varies, are provided in Figures 1, 2 and 3.

### SYSTEM MODEL DETAILS

The simple system consists of a 4 kV voltage source connected to a 100 HP, 4 kV induction motor. A range of positive and negative sequence voltages were simulated, with the positive sequence ranging from 1 pu to 0.5 pu, in steps of 0.01, while the negative sequence at the same time ranged from 0pu to 0.5 pu, also in steps of 0.01. High levels of unbalance, where V1=V2=0.5, would represent an open phase condition, where one phase is physically disconnected.

The induction motor model parameters are listed in Table 1.

**Table 1 – Induction Motor Parameters**

| Parameter | Value | Units |
|---|---|---|
| Rated Horsepower | 100 | HP |
| Rated Voltage | 4 | kV |
| f | 60 | Hz |
| Number of Poles | 4 | |
| Full Load Slip | 1 | % |
| Efficiency | 90 | % |
| Power Factor | 90 | % |
| Break Horse Power | 115 | % |
| Locked Rotor Current | 6.5 | pu |
| Starting Torque | 0.7 | pu |
| Moment of Inertia | 0.1 | pu |

The induction motor EMT model motor type is a single squirrel cage with Deep bar factor.

## RESULTS

The phase motor currents from the two modeling program simulations during increasing levels of voltage unbalance are shown in Figures 1, 2 and 3. From the figures below, it is obvious that the phase current magnitudes diverge at high levels of unbalance. Notably, the unbalanced load flow software shows phase B current becoming negative at 40% unbalance. Additionally, the motor stalling behaviour can clearly be observed at approximately 60% unbalance in the EMT results, whereas no clear stall point was observed in the steady-state unbalanced load flow result.

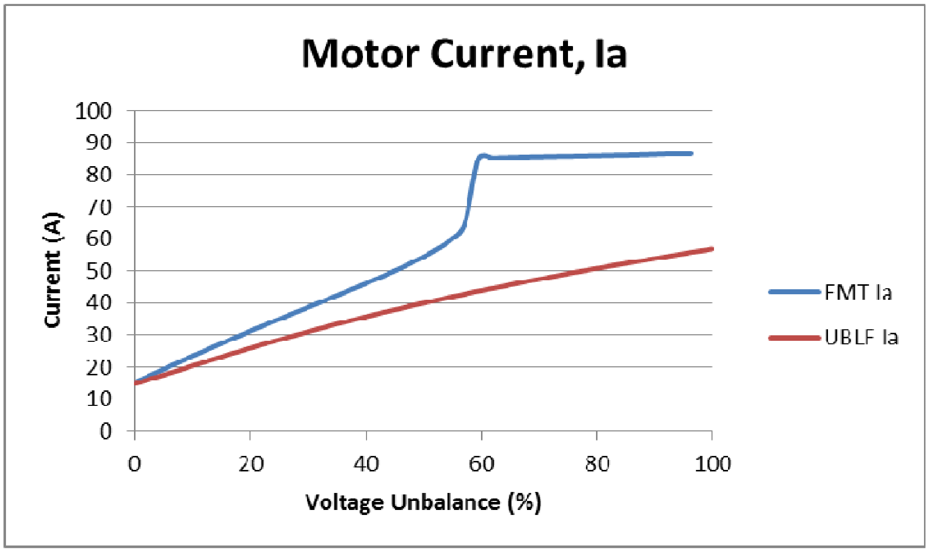


**Figure 1 Induction Motor Phase A Current from the EMT-type and Unbalanced Load Flow Simulation Results**

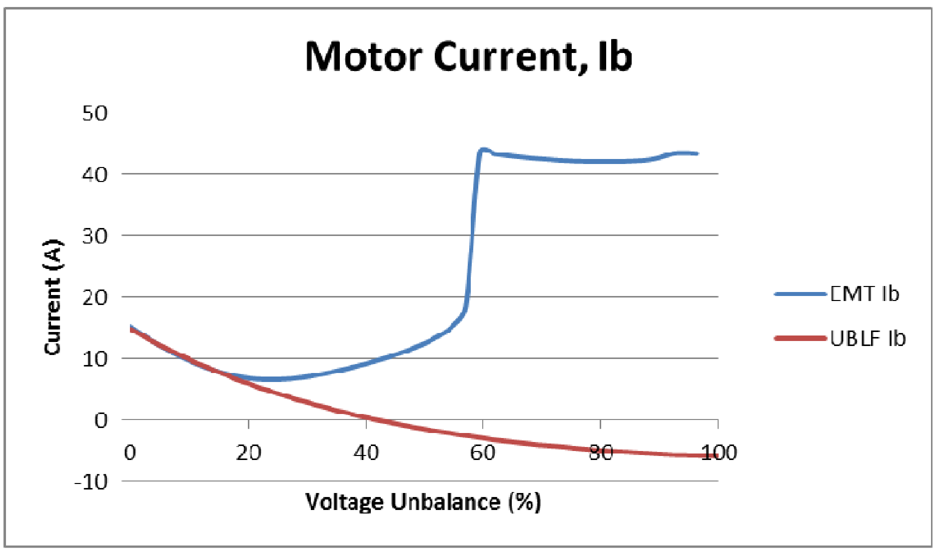


**Figure 2 Induction Motor Phase B Current from the EMT-type and Unbalanced Load Flow Simulation Results**

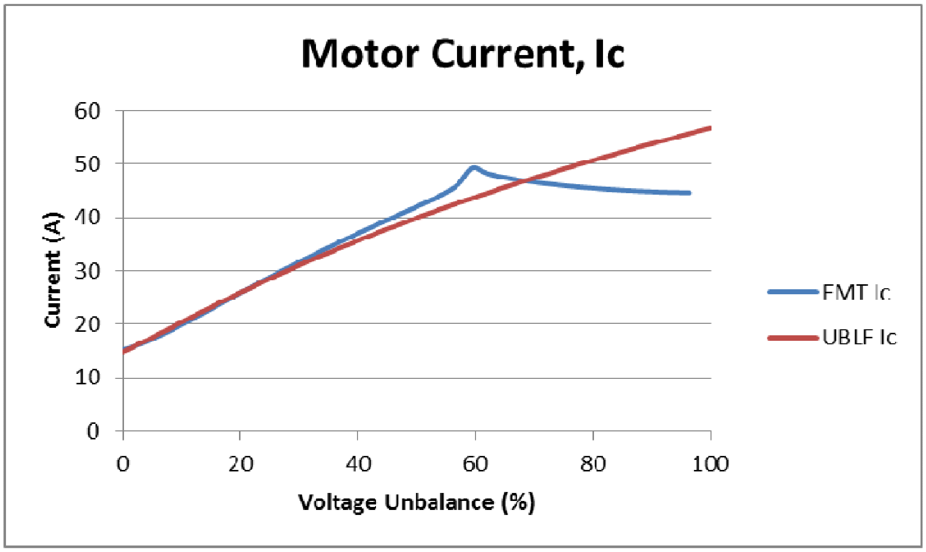


**Figure 3 Induction Motor Phase C Current from the EMT-type and Unbalanced Load Flow Simulation Results**

## CONCLUSION

An induction motor load operating under voltage unbalance conditions was modeled in a commercial steady-state unbalanced load flow software package and in a commercial EMT-type software package. The voltage unbalance was varied over a wide range of possible operating conditions. The resulting motor phase current magnitudes from each software package are compared.

The results show that with increasing levels of voltage unbalance, the motor behavior diverges significantly in the two different software packages. Furthermore, the steady-state unbalanced load flow software is unable to predict motor stalling. Based on the results, it is recommended that EMT-type software be used for induction motor modelling during voltage unbalance.

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