Detection of Voltage Unbalance on Three Phase Induction Motor Using Artificial Neural Network

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Abstract

Power quality problem such as unbalanced voltage have adverse effects on the satisfactory performance of three phase induction motors which are the main work horses in many industrial, commercial and residential applications. The new models of three phase induction motor and adjustable speed drives are highly susceptible to unbalance voltage. Detecting whether the supplied voltage to these machine is balanced or unbalance is very vital, if the service life and motor efficiency will be maintained for a reasonably numbers of years. This paper applied Artificial Neutral Network for detection of voltage unbalance. ANN was satisfactorily trained with 100 samples of real-time voltage readings supplied to three phase induction motors. The collected data were the fed to the trained ANN for classification. The results of the analysis showed that 26.25% were detected to be balanced voltage while 73.75% were tagged unbalanced. It was observed that Mean Squared Error (MSE) was found to be 0.084321, Root Mean Squared Error (RMSE) was found to be 0.781885 and percentage accuracy was 100% for balanced and unbalanced voltage.

Key words: Artificial Neutral Network, Induction Motor, Poly-Phase System, Power Quality, Voltage Imbalance

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INTRODUCTION

Nowadays, induction motors being a typical example of complex electromechanical devices are the main work horses in many industrial, commercial and residential applications [1], [2]. This is largely due to numerous techno-economic benefits such as ruggedness, high reliability, low cost of purchase and maintenance, small-sized with high efficiency and the ease of operation with any available power supply [3]. Good self-starting capability in addition to those salient features mentioned earlier enhanced the suitability of large three phase induction motors in the generation of electricity [4]. However, several factors such as hostile environments, operational deficiency, manufacturing defects among others subject these motors to internal faults like inter-turn short circuits, ground faults, differs mechanical failures and external faults such as mechanical overloads caused by prolonged starting / locked rotor and stalling, unbalanced supply voltage, phase sequence reversal of supply voltage etc. [3], [5], [6].

The source of electrical power supply to many electrical devices / drives including induction motors has being the poly-phase system; with this system of supply, each phase voltage is designed to be at the same magnitude, this is feasible at generation and transmission levels but far from reality in distribution end of power system [7], [8]. At utilization levels, unequal system impedances and the unequal distribution of single phase loads caused each supply phase voltage to be unbalanced [8]. Voltage imbalance / unbalance constitutes a serious power quality problem and no matter how minute the level of voltage unbalance, newer models of induction motors and adjustable speed drives (ASD) are very sensitive to its effects compared to previous version of induction motors [7], [8], [9].

Principal causes of voltage unbalance are uneven distribution of single-phase loads, malfunctioning of power factor correction equipment, harmonics due to electronics equipment, asymmetrical transformer winding impedances, open wye and open delta transformer banks, asymmetrical transmission impedances probably caused by partial transposition of transmission lines, and blown fuses on three-phase capacitor banks [10], [11], [12]. The nature of unbalance could take the form of unequal voltage magnitudes at system fundamental frequency (under-voltages and over-voltages), fundamental phase angle deviation, and unequal levels of harmonic distortion between the phases [13]. The adverse consequences of unbalance voltage on induction motors and energy-saving schemes such as adjustable speed drive (ASDs) among others include high unbalanced phase currents, Derating of poly-phase induction motors, reduced motor torque and speed, increased noise and vibration, reduction in overall motor efficiency and usable service-life [10], [14], [15]. Early detection of unbalance voltages fed to these heavily used industrial motors is vital as it helps to reduce revenue losses incurred in the event of faults clearing and it as well reduces the number down time due to unexpected machine faults.

In recent years, several studies had been carried out by researchers on different alternatives means of detecting and classifying various types of faults in induction motor. An extensive review on the use of artificial neural network (ANN) techniques for identifying induction motor faults was presented [16]. ANN was applied for diagnosis and monitoring of external abnormalities in induction motor [17]. Wavelet transform and principal component analysis (PCA) based on support vector machine (SVM) was used for early detection of voltage unbalance in three phase induction motor [18]. PCA approach was used by [19] to select proper input for neural network based technique for fault detection. Wavelet decomposition and feed forward neural was used as fault classifier in diagnosis of induction motor faults [20]. Fast classification of faults in an induction motor using artificial neural network and PCA was presented by [21].

This paper proposes a method for detection of voltage unbalance on three phase induction motor using Artificial Neural Network. Samples of real-time voltage readings of three phase induction motors collected from Evans Nigeria Limited were used for the analysis.

DEFINITIONS OF VOLTAGE IMBALANCE

Several researchers had attempted to define voltage imbalance. However, definitions relating to line voltage unbalance, phase voltage unbalance and negative sequence unbalance factor among all shall be reviewed in this paper. They are IEEE Std 141, National Electrical Manufacturers Association Motor and Generator Standard (NEMA MG1.1993) and Negative Sequence Voltage Unbalanced Factor. IEEE Std 141, defines voltage imbalance in relation to phase voltage unbalance in percentage (PVUR) at machine terminals [22];

$$PVUR = \frac{\max\left[\left|V_a - \frac{V_a+V_b+V_c}{3}\right|, \left|V_b - \frac{V_a+V_b+V_c}{3}\right|, \left|V_c - \frac{V_a+V_b+V_c}{3}\right|\right]}{\frac{V_a+V_b+V_c}{3}} \times 100\% \quad (1)$$

where; V_a , V_b and V_c represents phase voltages

National Electrical Manufacturers Association Motor and Generator Standard gave its own definition of voltage unbalance with respect to Line Voltage Unbalance in Percentage (LVUP) at the machine terminal [23];

$$LVUP = \frac{\text{maximum voltage deviation from average line voltage}}{\text{average line voltage magnitude}} \times 100\% \quad (2)$$

$$LVUP = \frac{\max\left[\left|V_{ab} - \frac{V_{ab} + V_{bc} + V_{ca}}{3}\right|, \left|V_{bc} - \frac{V_{ab} + V_{bc} + V_{ca}}{3}\right|, \left|V_{ca} - \frac{V_{ab} + V_{bc} + V_{ca}}{3}\right|\right]}{\frac{V_{ab} + V_{bc} + V_{ca}}{3}} \times 100\% \quad (3)$$

IEC 60034-26 defines voltage unbalance with respect to Negative Sequence Voltage Unbalanced Factor given in [24] thus;

$$VUF (\%) = \frac{\text{Negative sequence voltage component magnitude}}{\text{Positive sequence voltage component magnitude}} \times 100\% \quad (4)$$

$$VUF (\%) = \frac{V_2}{V_1} \times 100\% \quad (5)$$

where; V_1 and V_2 are the positive and negative sequence phase voltage components.

Applying Fortescue transformation in the complex plane as follow;

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (6)$$

Then;

$$V_1 = \frac{V_{ab} + aV_{bc} + a^2V_{ca}}{3} \quad (7)$$

$$V_2 = \frac{V_{ab} + a^2V_{bc} + aV_{ca}}{3} \quad (8)$$

where; V_{ab} , V_{bc} and V_{ca} represents line -to-line voltages

MATERIALS AND METHODS

The data used for this research were real-time voltage readings of three phase induction motors collected from Evans Nigeria Limited. The data was collected for 9 days, between 8-18th October, 2015. The duration for data collection for the first seven days spans between 9.00am to 16.00pm and for the last two days, duration spans from 20.00 pm to 7.00 am.

Detection of Unbalance Voltage using Artificial Neural Network (ANN)

ANN is artificial intelligence techniques that are widely employed in information-processing applications. Its information processing style is founded on human biological nervous systems. It is a set simple processing interconnected unit that multiplies the values which go through them via assigned weights. Prediction with ANNs involves two steps: supervised training and learning. The neural network is trained so that it can recognize the output pattern that corresponds to the input pattern.

Also, weights modification in accordance to a learning rule is equally possible, this enhance input-output pattern recognition. The most widely used ANN structure is the feed-forward network and was employed in this paper. ANN was satisfactorily trained with 100 samples of real-time voltage readings supplied to three phase induction motors. In this paper, an unbalance voltages are those that are below 330 V, it was labelled ‘-1’ while balance voltages are those between 330 V and 420 V, it was labelled ‘1’. These are the target labels used for training the ANN. The performance evaluation of trained ANN was done using Mean Squared Error (MSE), Root Mean Squared Error (RMSE) and Classification/detection accuracy as performance metrics.

Mean Squared Error: This give a measure of the difference between the actual classifications and the ANN classifications, a very low MSE value indicates that the ANN is well trained and vice-versa.

$$MSE = \frac{1}{N} \sum_{i=1}^N (A(i) - P(i))^2 \quad (9)$$

where;

$A(i)$ = the actual classifications

$P(i)$ = the predicted classifications

Root Mean Squared Error (RMSE): The RMSE is a function of the MSE, it is expressed as:

$$RMSE = \sqrt{MSE} \quad (10)$$

Classification Accuracy: The classification accuracy of the ANN is measured in percentage. It is expressed as;

$$Accuracy = \frac{K-IC}{K} \times 100 \% \quad (11)$$

where; K = total tested samples; IC = number of incorrect classification.

The parameters for ANN training is presented in Table 1;

Table 1: The ANN Training Parameters

The ANN Training Parameter	
Architecture	2-layer (1 hidden layer and 1 input)
Training algorithm	Feed forward Back-propagation neural network (BPNN)
Transfer function	tansig, purelin
Maximum training epoch	10^2
Performance function	Mean-Squared Error (MSE)
Performance goal	$1e^{-4}$
Hidden neurons	10

Algorithm for Training ANN

The algorithm for ANN training is presented below;

Step 1: Start

Step 2: Load the training input data (voltage unbalance and balance readings with target labels)

Step 3: Normalize input data (i.e set data between -1 and 1)

Step 4: Create the ANN object (feed forward back-propagation neural network)

Step 5: Train the ANN object with the input data

Step 6: Save the trained ANN object for online detection of voltage unbalance

Step 7: End

Also, the testing of the created ANN object involves the use of voltage readings that were not part of the training database. The voltage readings are passed into the ANN object for classification between Balance (-1) and Unbalance (1). If the ANN outputs '-1' the detected voltage is tagged Balance, but if the ANN outputs '1' the voltage detected is tagged Unbalance.

The Algorithm for Testing Trained ANN

The algorithm for ANN testing is as presented below;

Step1: Start

Step 2: Load the created ANN object

Step 3: Load the voltage supply readings on the 3- ϕ machine (New readings)

Step 4: Normalize the voltage data

Step 5: Simulate the ANN object with data to detect voltage unbalance on the line

Step 6: Display result of detection

Step 7: End

RESULTS AND DISCUSSION

The proposed approach was implemented MATLAB/SIMULINK, it was run on a portable computer with an Intel Core2 Duo (1.8GHz) processor, 2GB RAM memory and MS Windows 7 as an operating system. After the completion of training process the result obtained is as presented in Table 2. From Table 2, the classification accuracy is very good and value of MSE is relatively low showing that ANN was trained to recognize corresponding input-output pattern.

Table 2: Results of ANN Performance for Voltage Imbalance Detection (Normal Condition
Rated Voltage of Motor: 330V-460V)

	Training (computer generated data)	Testing (Real-time data)
Number of test voltage samples	50	80
Percentage Correct classification	100.000%	100.000%
Percentage Incorrect classification	0.000%	0.000%
Mean-Squared Error (MSE)	0.012150	0.084321
Root mean-squared error (RMSE)	0.110228	3.887484
Total processing time(seconds)	3.9688	

The total tested voltage samples were 80, 26.25% were detected to be balanced while 73.75% were tagged to be unbalanced. All sampled voltages on Dec., 8, 10, 11, 14, 15 were ANN detected to be unbalanced, Dec., 18 sampled voltages were detected by ANN to be balanced while the rest days sampled voltages consist of both balanced and unbalanced voltages. The graphical representation of training, testing and validation is as shown in Figure 1;

Figure 1: Graphical Representation of Training, Testing and Validation

The graph of Mean Square Error against the 35 epochs (iterations) were as well obtained, it was observed that the best validation performance was find to be 0.013507 and this occurred at epoch 29. Its graphical representation is as shown in Figure 2 below;

Figure 2: The Graph of Mean Squared Error against the 35 epochs (iterations)

The summary of the proposed approach for detection of unbalanced voltage is presented in Figure 4; a cursory examination of results presented showed that level of unbalanced voltage supplied to power the induction motors in this industry is higher compared to balanced voltage supplied.

Figure 4: A Bar Chart Showing Comparison of Balanced Voltage, Unbalanced Voltage and Tested Sample Voltage

CONCLUSION

Detection of voltage imbalance on three phase induction motor using Artificial Neural Network was presented in this paper. Feed-forward network structure of ANN was employed and after satisfactory training of ANN, the dataset required to be classified was fed to ANN for classification based on target set (Balanced and Unbalanced Voltage). The results of the analysis showed that 26.25% were detected to be balanced voltage while 73.75% were tagged unbalanced. It is observed that for five processing elements in hidden layer MSE is 0.084321 and percentage accuracy is 100% for balanced and unbalanced voltage. Critical examination of the study area revealed that several factors such as uneven distribution of single-phase loads and malfunctioning of power factor correction equipment among others are major cause of unbalanced in the supply voltage magnitude fed to the company three phase induction motors. Detection of healthy and unbalanced voltage with this scheme using ANN is a simple, reliable and efficient protection setup.

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