Comparison between Direct-On-Line, Star-Delta and Auto-transformer Induction Motor Starting Method in terms of Power Quality

H.H. Goh, M.S. Looi, and B.C. Kok

***Abstract*—This paper presents a comparison between the Direct-On-Line (D.O.L.), Star-Delta, and Auto-transformer induction motor starting method in terms of power quality. The purpose of this research is to find out the most reliable and practical starting method which has the less power quality problems. These three basic starting methods which differ in their respective wiring connection are the most applicable and widely-used starting method in the industrial area due to its economic reasons. This research is done by analyzing the existed power quality events during the motor starting by using the Fluke Power Quality Analyzer to capture the waveforms of the events. After the experiments, the three different starting method are being compared to conclude the most suitable and applicable starting method which causes the least severe power quality events.**

***Index Terms*— Autotransformer, D.O.L., Power quality, Star-Delta.**

I. INTRODUCTION

THE rapid technological progression in these days, both of the electric utilities and end users of electric power are becoming increasingly concerned about the quality of electric power. The increasing emphasis on overall power system efficiency has resulted in continued growth application of devices such as high-efficiency, adjustable-speed motor drives and shunt capacitors for power factor correction to reduce losses. This causes the increases in harmonic levels on power systems and has many people concerned about the future impact on system capabilities [1]. The starting of large motors and their associated loads has always presented an electrical and equipment challenge [2]. The main reason that human are interested in power quality is economic value. Poor power quality may cause electrical appliances malfunction or fuses to trip. Most of these cases happen in the motor starting. During the motor starting, the major problem occurs is the disconnection of the motor itself due to the presence of the power quality problem (voltage sags). As a result, a study of the motor starting needs to be carried out to prove the power quality events. Therefore, the types of power quality events also need to be identified in accordance to the percentage of voltage variations. From this parameter, it can be concluded that whether the types of power quality events may disrupt the motor or affect the power system.

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II. RESEARCH BACKGROUND

Power Quality [3] is an issue between the compatibility of the supply systems and the loads. Probably the most widely recognized and studied effect of motor starting is the voltage dip that is experienced throughout an industrial power system as the direct result of starting large motors [4].

There are several general methods of starting induction motors: full voltage, reduced voltage, wye-delta, and part winding types. The reduced voltage type can include solid state starters, adjustable frequency drives, and autotransformers [5]. Motor starting has been investigated for decades [5-16].

The most frequent power quality events that occur are voltage sags and voltage transients as well as harmonics. Generally, voltage sags occur due to short-circuit faults, however, motor starting is also the main cause of the voltage sags. The starting of industrial-range motors draw a larger current than normal, typically ten times higher than usual, remains until the motor reaches in nominal speed, which takes several seconds to minutes. Evaluating these concerns requires measurement equipment that can capture the voltage sags waveforms over the full duration. The power quality analyzer/meter as well as other tools such as software implementation are need to monitor through the significant events even in just a few milliseconds of time, because the voltage sags is enough to trip a fuse, blinking the lighting systems or even disrupt sensitive equipment. A thorough and detail study of the motor starting should be carried out to identify the voltage sags and their characteristics respectively.

III. VOLTAGE SAGS IN MOTOR STARTING

Power quality events such as voltage sags and harmonics may occur in motor starting due to the inrush current. Inrush current occurs because the motor will draw six to ten times of current than usual to produce a starting torque. Voltage sags due to the starting of large motors can again be theoretically calculated similar to the one caused by system faults [17].

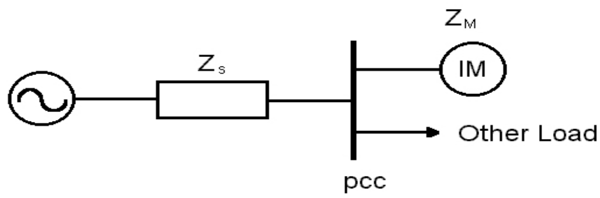

Fig. 1. Equivalent circuit for induction motor starting

The voltage at the PCC is given by the equation:

$$V_{sag} = \frac{Z_M}{Z_S + Z_M} E \qquad (1)$$

where Z_m is the impedance of the motor under study and Z_s is the source impedance. It is realized that these calculations are only for approximations but to have an accurate result of a voltage sag phenomena, a power system analysis package should be used [17]. Motor starting causes high inrush currents, and the absence of a good understanding of the inrush current which causes the power quality events may spoil the motor or affect the sensitive load at its surrounding.

IV. Motor Starting Method

Direct-On-Line Starter (D.O.L) Starting Method

This is the most common starting method available in the market. The components consist of only a main contactor and thermal or electronic overload relay. The disadvantage with this method is that it gives the highest possible starting current. A normal value is between 6 to 7 times the rated motor current but values of up to 9 or 10 times the rated current exist. During a direct-on-line start, the starting torque is also very high, and is usually higher than required for most applications.

Star-Delta Starter Starting Method

This is a starting method that reduces the starting current and starting torque. The components normally consist of three contactors, an overload relay and a timer for setting the time in the star-position (starting position). The motor must be delta connected during a normal run, in order to be able to use this starting method. The received starting current is about 30 % of the starting current during direct on line start and the starting torque is reduced to about 25 % of the torque available at a D.O.L start. This starting method only works when the application is light loaded during the start. If the motor is too heavily loaded, there will not be enough torque to accelerate the motor up to speed before switching over to the delta position. When starting up, the load torque is low at the beginning of the start and increases with the square of the speed. When reaching approximately 80-85% of the motor rated speed the load torque is equal to the motor torque and the acceleration ceases. To reach the rated speed, a switch over to delta position is necessary, and this will very often result in high transmission and current peaks. In some cases the current peak can reach a value that is even bigger than for a D.O.L start. Applications with a load torque higher than 50% of the motor rated torque will not be able to start using the star-delta starter.

Autotransformer Starter Starting Method

This is another starting method that reduces the starting current and starting torque but contrary to Star-Delta starting where this starting method needs three wires and three terminals on the motor. Autotransformers are generally equipped with taps at each phase in order to adapt the starting parameters to the application starting requirement. During starting, the motor is connected to the autotransformer taps. With the star and autotransformer contactors closed, the motor is under reduced voltage. Consequently the torque is reduced as the square of the applied voltage. When the motor reaches the 80 to 95% of the nominal speed, the star contactor opens. Then the line contactor closes and the autotransformer contactor opens. The motor is never disconnected from the power supply during starting (closed transition) and reduces transient phenomena. Taps on the autotransformer allow for selection of the motor with 50%, 65%, or 80% of the current inrush seen during a full voltage start. The resulting starting torque will be 25%, 42%, or 64% of full voltage values, as will be the current draw on the line. Thus, the autotransformer provides the maximum torque with minimum line current.

V. Experimental Works

The three types of motor starting method were carried out by using the laboratory workbench. The wiring connection of the motor starting was set up and being monitored by the Fluke Power Quality Analyzer.

Fig. 2. Laboratory Workbench for the Motor Starting Experiment

The laboratory testing for the different types of motor starting are based on the sequence of the flow chart as shown below:

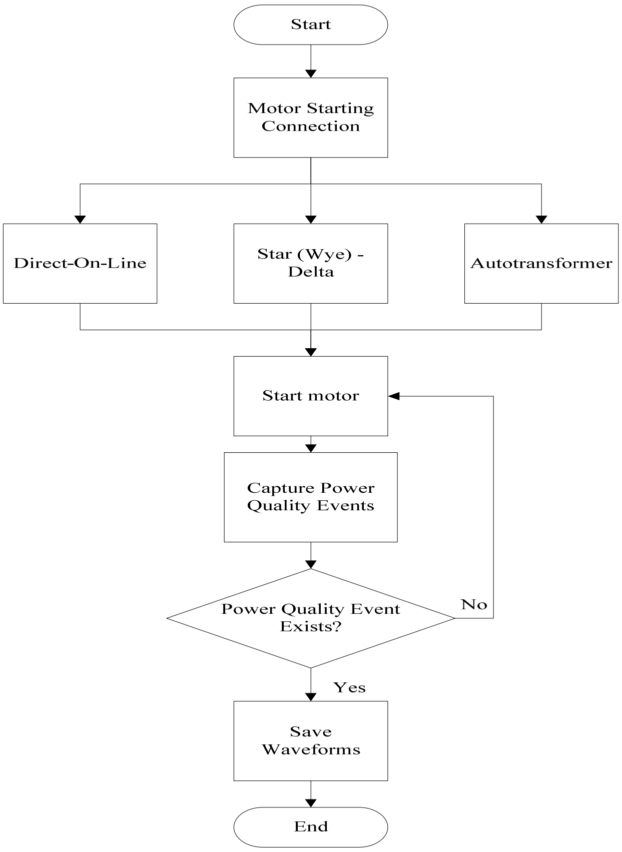

Fig. 3. Sequence of the Laboratory Testing For Motor Starting

VI. Preliminary Results and Data Analysis

The causes of the unbalanced three-phase waveforms are being analyzed with respective to its motor starting method.

A. Direct-On-Line Starter (D.O.L)

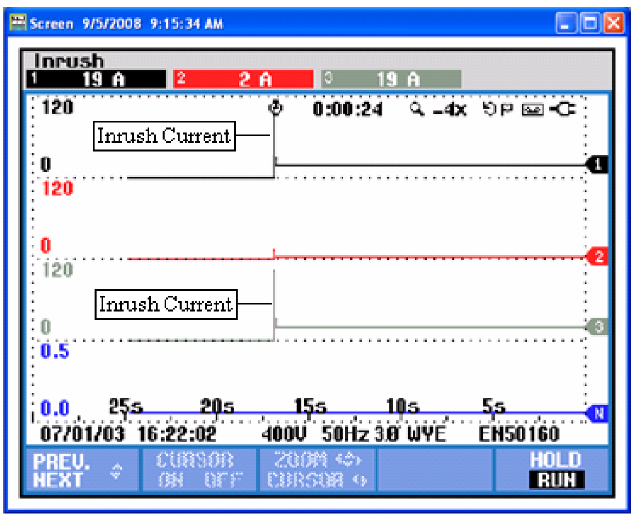

Fig. 4. Inrush Current in DOL Starting

Fig. 4 shows the inrush current occurs in the induction motor starting. The inrush current causes the voltage at the motor terminals to drop in magnitude. In this condition, the magnetic flux in the air gap is no longer in balance with the stator voltage. The flux decays with a time constant of up to several cycles, apparently with the voltage at the motor terminals. The decay in voltage causes the drop in electrical torque which causes the motor slows down. As the motor slows down it draws larger current with a smaller power factor. This will bring down the voltage even more. The voltage will slowly recover and opposite phenomena occur. At the moment when the voltage recovers, the flux in the air gap will build up again. This causes the large inrush current, which slows down the voltage recovery. After that, the motor will re-accelerate until it reaches its pre-event speed. During the re-acceleration the motor again takes a larger current with a smaller power factor, which causes post-fault voltage sag sometimes lasting for a several seconds. The starting current for an induction motor can be calculated by using the formula as stated in equation (3) [18];

$$S_{start} = \text{(rated horsepower) (code letter factor)} \qquad (2)$$

The starting current is

$$I_L = \frac{S_{start}}{\sqrt{3}\, V_T} \qquad (3)$$

Where V_T is the terminal voltage of the induction motor
The induction motor in this project is rated as followed:

Rated horsepower = 2hp

Code Letter Factor = F (5.60 kVA/hp)
Terminal Voltage, V_T = 415 V

S_{start} = (rated horsepower) (code letter factor)
= 2hp × 5.60 kVA/hp
= 11.2 kVA

$$I_L = \frac{S_{start}}{\sqrt{3}\, V_T} = \frac{11.2\ kVA}{1.732 \times 415}$$
= 26.98A

Thus, the starting current is 26.98A. Apart from that, the β, ratio between the starting current and the nominal current must be determined.

$$\beta = \frac{\text{Starting Current}}{\text{Nominal Current}} \qquad (4)$$
$$\beta = \frac{26.98\ A}{3.75\ A}$$
$= 7.19 \approx 7$

From this equation, this shows that the inrush current, which is similar to the starting current is 7 times higher than the nominal rated current which is 3.75 A.

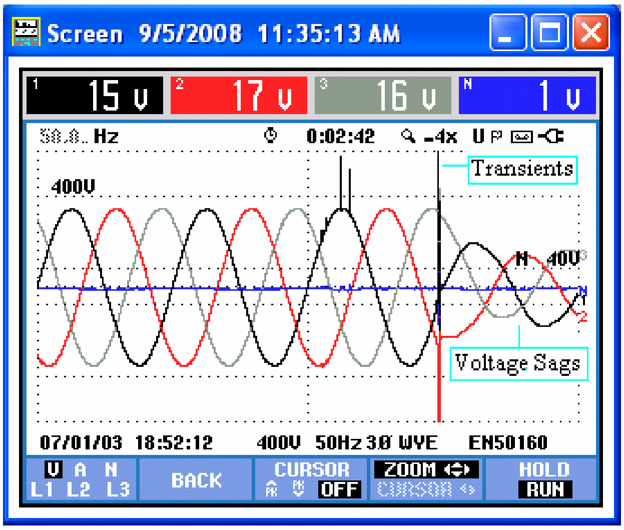

Fig. 5. Voltage Sag in DOL Starting

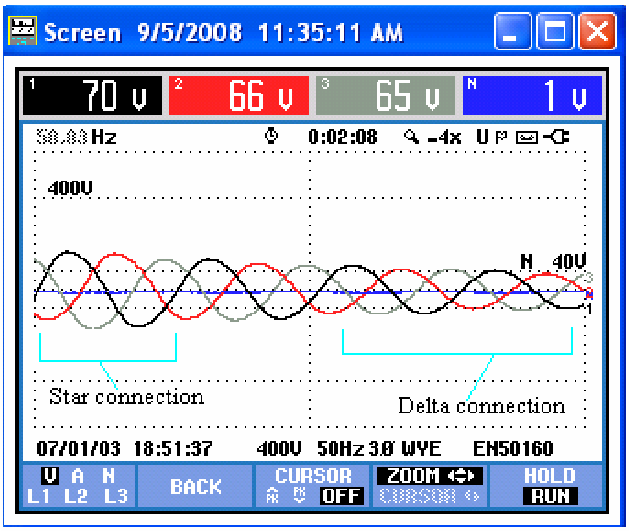

Fig. 6. Voltage Sag in Star-Delta Starting

As the consequences of the high inrush current in the motor starting, the voltage sag occurs as depicted in Fig. 5. These events which occurred can be explained by applying Ohm's and Kirchoff's Laws in equation (5).

By applying Ohm's Law,

$$V = I \times Z \quad (5)$$

where V is the Voltage, I is the Current, and Z is the Impedance. The Kirchoff's Voltage Law states that the sum of voltages around a closed loop must equal to zero. The motor starting system has 1Ω source impedance and a 26.98A starting current on a 415V system, the inrush current can result in a drop of 26.98 V. Therefore, voltage at the load would sag to 388.02V, down from the nominal 415V level. This sag occurs because the impedance of the motor initially (when the rotor is stationary) acts as a short circuit. Once the rotor starts turning, the current decreases and eventually goes to a much lower, steady-state value. However, if a load change causes the motor to come close to stalling or remain in the locked rotor condition, once again voltage sag can result for similar reasons.

B. Star-Delta Starting

In the star-delta starting method, the wiring connection from the power supply source to the motor is connected from star (wye) to the delta connection. The motor is started in star configuration and then it is transferred to the delta configuration, allowing the full voltage to be applied to the motor during its running so as to get the full torque output. This can be further explained that in a Star-Delta starter, the motor is started as star connection and when the motor starts running the connection is changed to delta. With star connection, the motor takes $\sqrt{3}$ times less voltage. However, as the torque is proportional to square of the voltage, the starting torque also reduces. During the transition from star (wye) to delta connection, the power quality events will occur which will be discussed in this section [18].

Fig. 6 shows the voltage sag in the Star-Delta starting. This event occurs during the transition from the Star (wye) connection to the Delta connection. During the transition moment, the contactor switches and causes the voltage to breakdown for an approximately of 0.25 seconds and this is enough to cause the voltage sag to occur in the motor starting. However, this is not the significant problem which does not affect the acceleration and torque of the motor starting. Once the connection to delta is established, the motor will accelerate until its nominal speed and thus, the voltage and current waveforms would be in stable manner.

C. Autotransformer Starting

In this project, the type of the connection of the autotransformer starter is the closed transition starter because the open transition switching may result in very high current and torque transients. This method is also known as the Korndoffer starter, which is connected to the 50% tap of the transformer. However, this starting method also yields high voltage and current transients.

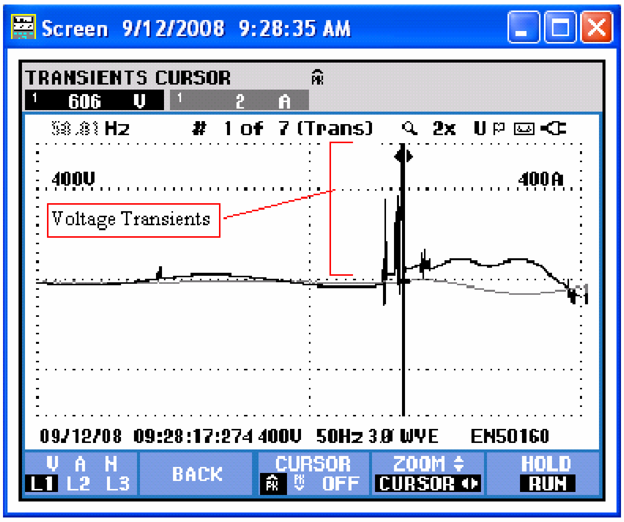

Fig. 7. Transients in Autotransformer Starting

Fig. 7 shows the occurrence of the transients during the autotransformer switching. This is caused by the transformer energizing before it reaches the 50% tapping, the time before the tap contactors open to disconnect the motor from the transformer and another contactor closes connecting the motor to the supplies. This can be explained; when the transformer is energizing, it produces inrush currents that are rich in harmonic components for a certain period. Hence, an overvoltage waveform appears caused by the third harmonic resonance in the wiring circuit. The third harmonic and Total Harmonics Distortion will be discussed in the next section. After the initial transient, the voltage again swells to nearly 150% for many cycles until the losses and load damp out of the oscillations.

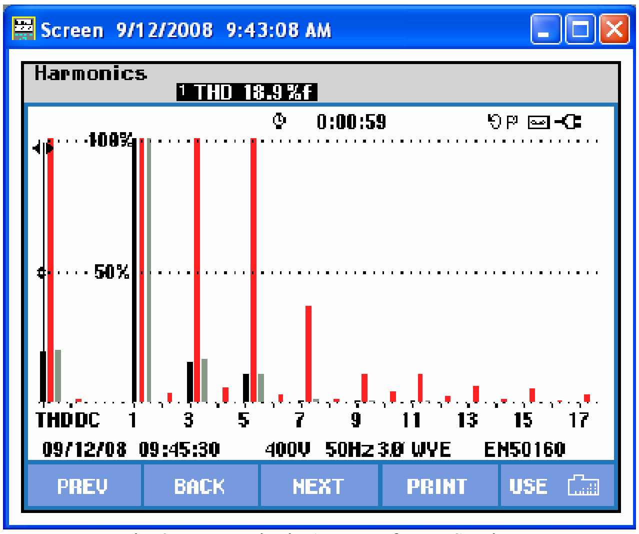

Fig. 8. Harmonics in Autotransformer Starting

The histogram illustrated in Fig. 8 above is regarding the harmonics in autotransformer starting. In this harmonic analysis, the triplen harmonics which are the 3rd, 9th, 15th and the others are being emphasized because the system response is often considerably different for triplens than for the rest of the harmonics because the motor is star connected where this triplen harmonics will flow to the neutral [1]. For the autotransformer winding connections in this project, it is star (wye) connected, which have a significant impact on the flow of the triplen harmonics current. These triplen harmonics current which are in phase, entering the wye side will add up in the neutral. The delta winding in motor terminal provides the ampere-turn balance so that they can flow, but remain trapped in the delta and do not show up in the line currents on the delta side. However, when the currents are balanced, the triplen harmonic currents behave as zero-sequence currents. The triplen harmonic currents shown above are the moment before the transformer tapping, where the triplen harmonic currents as such high which freely circulate in the wye side, causes the Total Harmonics Distortion as much as 18.9%. After the transformer tapping takes place, the triplen harmonic currents will reduce to the lowest, when the currents are in balanced condition.

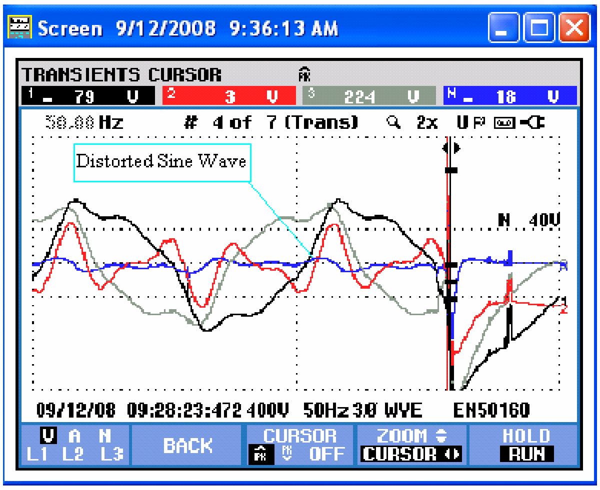

Fig. 9. Waveform Distortion caused by Harmonics

Fig. 9 shows the distorted sine wave in the autotransformer starting. This event occurs due to the harmonic currents when energizing the transformer. As can be seen on the histogram harmonics in the Figure 8, the 3rd and the 5th are the highest harmonics current. These harmonic orders exhibit the highest peak levels of high voltage systems, causing the unbalanced voltage in the motor starting. Obviously, it can be observed from Fig. 9 that the three-phase voltage differs considerably, ends up with a transient during the starting of the motor before it reaches the tapping sequence of the transformer. Once the motor has reached full speed, the star (wye) contactor is opened effectively converting the autotransformer starter into the primary reactance starter. At this moment, this waveform distortion occurs, until the primary reactance is bridged by a contactor applying full voltage to the motor.

TABLE I

COMPARISON OF THE MOTOR STARTING METHOD

Criteria	Direct-On-Line	Star-Delta	Autotransformer
Inrush Current	High	Low	Low
Voltage Sags	Severe > 0.5 p.u.	Less Severe < 0.2 p.u.	Less Severe < 0.2 p.u.
Harmonics	Less (THD < 1%)	Less (THD < 1%)	Severe during starting (THD = 18.9%)
Transients	Severe	Less Severe	Severe

From the TABLE I, the comparison had been made and it is clearly shown that the Star-Delta starting method had the least power quality problems occur. However, although these power quality events occurs, but it is not capable enough to trip the contactor or fuses because the comparison made is for the low power rated induction motor, which lies in the class below the 3hp of the output power for the motor.

This had proved that the power quality events still occur in the motor starting, just differ in the severity of the inrush currents and also the harmonics which made the motor still can be safely started without disrupting other sensitive loads.

VII. Conclusion

This paper has presented a few practically efficient methods for power quality data analysis as well as some initial findings of the most reliable method which yields the least power quality issues on motor starting circuits. The Star-Delta starting method yields the least power quality problems compare to D.O.L. and Autotransformer starting. This comparison is valid for the low power rated motor which is less than 3hp or 2.2kW of the motor output power rating. However, in the higher output power rating motors, this comparison may not be suitable. The proposed method has been implemented for analysis and categorization of power quality data collected. Results are given to illustrate the effectiveness and robustness of the proposed method in power quality. More work is currently in progress to validate the proposed tool, which will be reported in near future.

VIII. Acknowledgement

The authors gratefully acknowledged the staffs in the Laboratory of Electric Machines and Drives as well as Laboratory of Electric Power, UTHM for their valuable contributions towards the success of this work. The authors would like to thank the Research and Innovation Centre, UTHM for financially supporting this research under the short grant.

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