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A Study of Induction Motor Starting Methods In Terms of Power Quality

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***Abstract*— This paper presents a comparison between the Direct-On-Line, Star-Delta, and Auto-transformer induction motor starting method in terms of power quality. The purpose of this research is to identify the most reliable and practical starting method with fewer power quality problems. These three basic starting methods which differ in their respective wiring connections are the most applicable and widely-used starting methods in the industrial area for its economic reasons. This research was produced by analyzing the existing power quality events during motor starting by using the Fluke Power Quality Analyzer to capture the waveforms of the events. Hence, the most suitable and applicable starting method which causes the least severe power quality event can be identified.**

Keywords: Autotransformer, Direct-On-Line, Harmonics, Power quality, Star-Delta

I. INTRODUCTION

RAPID technological progression today, of both 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 multi application of devices such as high-efficiency, adjustable-speed motor drives and shunt capacitors for power factor correction to reduce losses. This causes increases in harmonic levels of power systems and has many people concerned about the future impact on system capabilities [1]. The main reason the public are interested in power quality is economic value. Poor power quality may cause electrical appliances to malfunction or fuse to trip. Most cases occur when the motor starts and during the process, the major problem is the disconnection of the motor itself due to the presence of the power quality problems. As a result, a study of the motor starting needs to be conducted 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 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 is an issue about the compatibility of supply systems and loads. 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 voltage sags. The starting of industrial-range motors draws a larger current than normal, typically ten times higher than usual remained until the motor reaches nominal speed, which takes several seconds to minutes [2]. Evaluating these concerns requires equipment that can capture the voltage sags waveforms over the full duration. The power quality analyzer and other tools such as software implementation are needed to monitor the significant events even in just a few milliseconds, because the voltage sags enough to trip a fuse, blinking the lighting systems or even disrupt sensitive equipment. A thorough and detailed study as well as the simulation of the motor starting should be conducted to identify and verify the power quality events and their characteristics respectively.

III. POWER QUALITY EVENTS IN INDUCTION MOTOR STARTING

Power quality events such as voltage sags and harmonics may occur in starting motors due to the inrush current. This inrush current occurs because the motor draws 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 that caused by system faults [3].

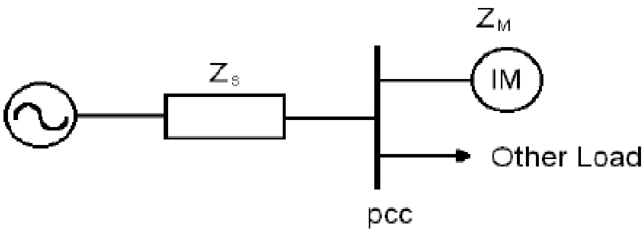

Fig. 1. Equivalent circuit for induction motor starting.

The voltage at the point of common coupling (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. These calculations provide approximations and an accurate result of voltage sag phenomena so a power system analysis package was used [3]. Motor starting causes high inrush currents. In understanding of high inrush current due to the motor starting is necessary required because the power quality events may spoil the motor or affect the sensitive load at its surrounding [4].

For harmonics analysis, the equivalent circuit of the three-phase induction motor with accurate frequency-based linear model is shown in Fig. 2. The subscript 1 denotes the fundamental frequency (h=1); ω_1 and s_1 are the fundamental angular frequency (or velocity) and the fundamental slip of the rotor, respectively. R_{fe} is the core-loss resistance, L_m is the linear magnetizing inductance, R_s,R_r',L_{sl},and L_{rl}' are the stator and rotor (reflected to the stator) resistances and leakage inductances, respectively. The value of R_{fe} is usually very large and can be neglected. The simplified sinusoidal equivalent circuit of an induction motor is shown below [5];

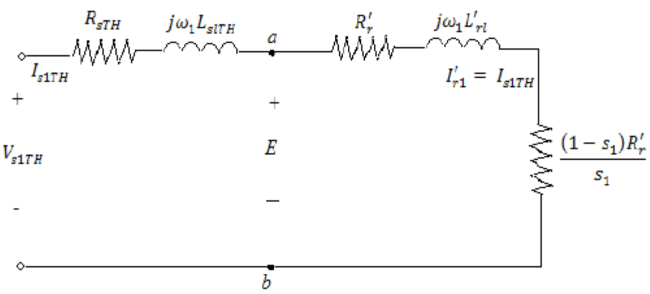

Fig. 2. Thevenin adjusted Equivalent Circuit of Three-Phase Induction Motor

The Thevenin-adjusted circuit is illustrated in Fig 2, the current of the *hth* harmonic is

$$I_{shTH} = \frac{V_{shTH}}{(R_{sTH} + \frac{R_r'}{s_h}) + jhw_1(L_{s1TH} + L_{rl}')} \qquad (2)$$

$$T_{eh} = \frac{1}{w_{sh}} \frac{q_1 V_{shTH}^2 \frac{R_r'}{s_h}}{(R_{sTH} + \frac{R_r'}{s_h})^2 + (hw_1)^2 (L_{s1TH} + L_{rl}')^2} \qquad (3)$$

Similarly, the fundamental (h=1) torque is

$$T_{e1} = \frac{1}{w_{s1}} \frac{q_1 V_{shTH}^2 \frac{R_r'}{s_h}}{(R_{sTH} + \frac{R_r'}{s_h})^2 + (w_1)^2 (L_{s1TH} + L_{rl}')^2}$$

If the harmonics order varies from 3, 5, 7 and others and is represented by h=3, 5 or 7, the torque of the induction machine will vary and this will cause the unbalanced torque when the rotor is spinning during the starting period.

IV. PREVIOUS RESEARCH

Previous researches in motor starting circuits in terms of power quality are done. Bong-Seok Kang, Jae-Chul Kim, Jong-Fil Moon, Sang-Yun Yun identified the various characteristics of voltage sags and temporary interruptions which can affect the functions of three-phase induction motors that are mostly used in the power distribution systems [6]. These assorted characteristics include the motor speed losses, voltage recovery, motor reacceleration, and transient characteristics. They implemented an experimental study on the induction motor behaviors to confirm these impacts. In addition, sequential voltage sags with short durations were considered and investigated. The results show that the occurrence of the second voltage sag after the first one may affects the induction motor adversely. Andrea Leira [7] used the EMTP to investigate the dynamic response of induction motors to voltage dips. The machine response is related to the voltage dip magnitude and duration. Dips represented include single and multi phase dips as well as sequential dips due to re-closing operations. The survivability of the motor operation is assessed against typical induction machine protection settings. It demonstrated that protection settings can be adjusted to improve the motor operation survivability of voltage dips without endangering the safety of the motor.

V. Experimental Results and Data Analysis

Fig. 3. Laboratory Workbench for the Motor Starting Experiment.

Figure 3 shows the setting up of the motor starting experiment. The experimental results of the three types of motor starting methods were carried out using the laboratory workbench. The wiring connection of the motor starting was set up and monitored by the Fluke Power Quality Analyzer. The three-phase voltage and current waveforms were analyzed respective to its motor starting method.

A. Direct-On-Line Starting

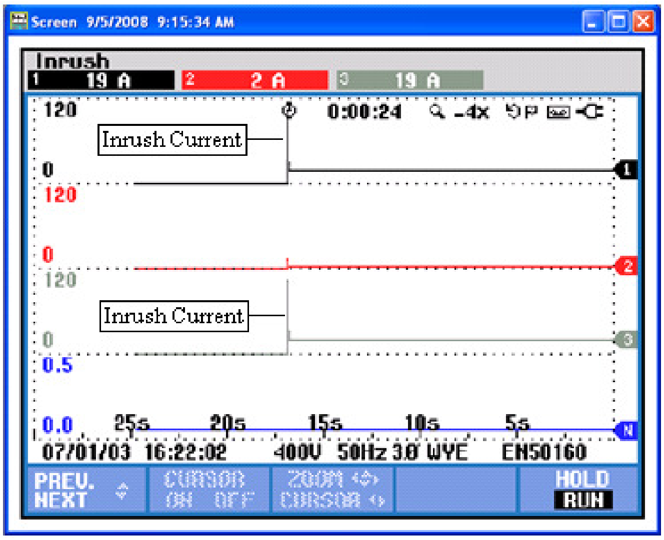

Fig. 4. Inrush Current in Direct-On-Line Starting.

Fig. 4 shows the inrush current to occur in 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 to slow down. As the motor slows, it draws larger current with a smaller power factor. This will reduce the voltage further. The voltage will slowly recover and an opposite phenomena occur. When the voltage recovers, the flux in the air gap builds up again causing the large inrush current and slowing the voltage recovery. The motor will re-accelerate until it reaches its pre-event speed. During re-acceleration the motor again takes a larger current with a smaller power factor causing the post-fault voltage sag sometimes last for several seconds [8,9].

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

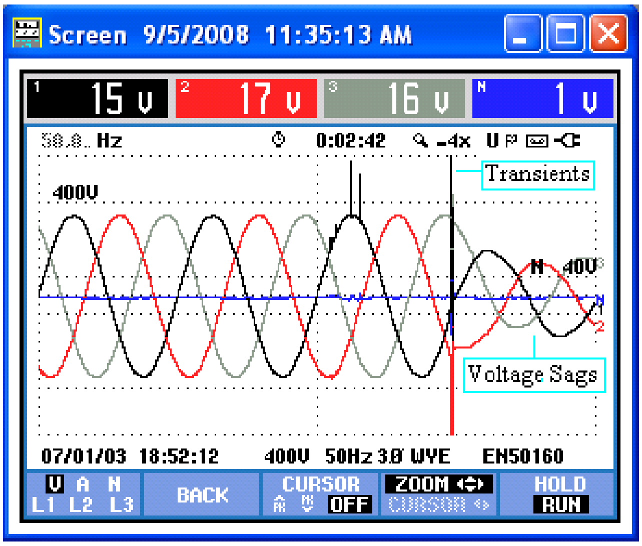

Fig. 5. Voltage Sag in DOL Starting.

By applying Ohm's Law,

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

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 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.

B. Star-Delta Starting

In the star-delta starting method, the motor is started as the star connection and when the motor starts running the connection is changed to delta. The motor takes 3 times less voltage with star connection. However, as the torque is proportional to the square of the voltage, the starting torque also reduces. During the transition from star to delta connection, the power quality events will occur. These will be discussed further [4].

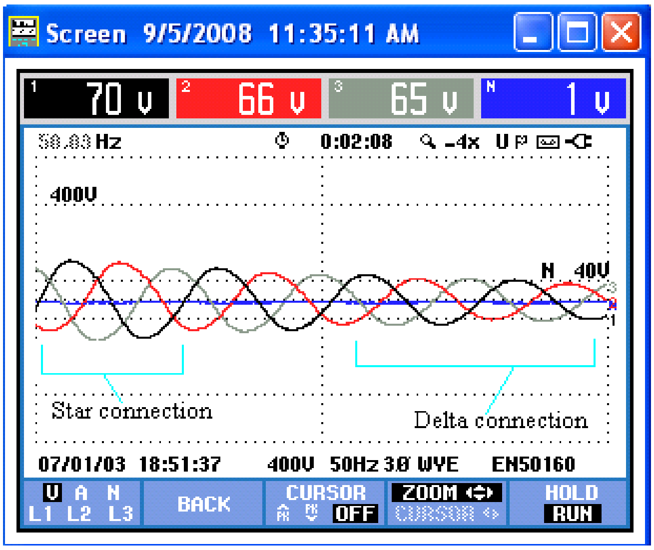

Fig. 6. Voltage Sag in Star-Delta Starting

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 approximately 0.25 seconds and is enough to cause the voltage sag to occur in the motor starting. Once the connection to delta is established, the motor will accelerate until its nominal speed so that the voltage and current waveforms are in stable manner [6].

C. Autotransformer Starting

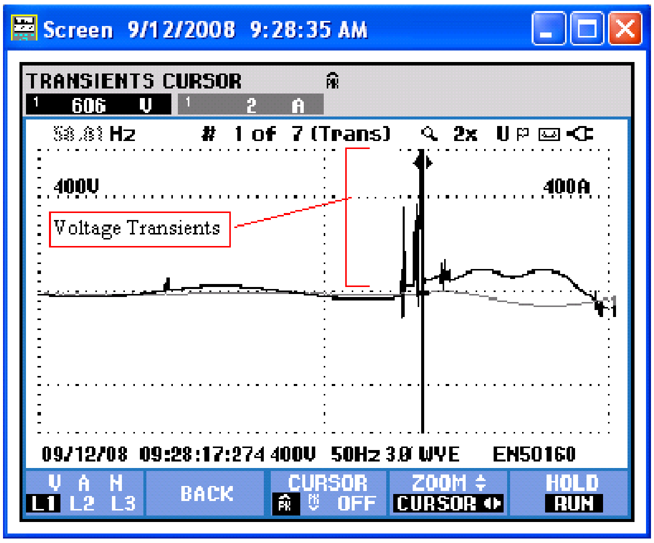

Fig. 7. Transients in Autotransformer Starting

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 with the transformer energizing to produce inrush currents that are rich in harmonic components for a certain period. Hence, an overvoltage waveform appears which is caused by the third harmonic resonance in the wiring circuit. After the initial transient, the voltage again swells to nearly 150% for many cycles until the losses and load damp out the oscillations.

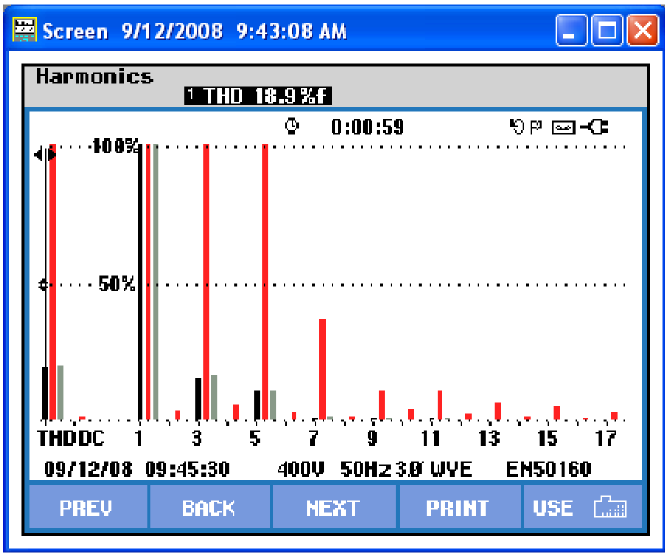

Fig. 8. Harmonics in Autotransformer Starting

The histogram illustrated in Fig. 8. presents harmonics in autotransformer starting. In this harmonic analysis, the triplen harmonics are the 3rd, 9th, 15th and others are emphasized because the system response is often considerably different for triplens than for the rest of the harmonics. This is because the motor is star connected where this triplen harmonics will flow to the neutral [1]. The autotransformer winding connections in this project are star (wye) connected and have a significant impact on the flow of the triplen harmonics current. These triplen harmonics current in phase entered the wye side adding up the neutral current. The delta winding in the 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 current at the moment before the transformer tapping takes place. 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 level, when the currents are in a balanced condition [6].

VI. Simulation Results and Discussion

These simulated circuits by using Power Systems Computer Aided Design/Electromagnetic Transients including DC (PSCAD/EMTDC) software yields almost the same results as being measured by the Fluke Power Quality Analyzer.

A. Simulation of Direct-On-Line Starting

Fig. 9 shows the Direct-On-Line circuit simulation by using the Power Systems Computer Aided Design (PSCAD) software. This starting method is almost similar with the real starting circuit, where the breaker in this circuit will act as the switch to turn ON and OFF the starting operation.

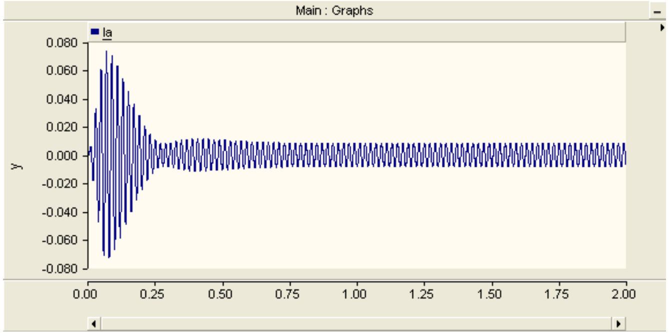

Fig. 10. The Inrush Current exists during the Direct-On-Line starting

Fig. 10 shows the high inrush current during direct-on-line starting. This waveform is the same as the real starting waveform measured previously. This shows that the direct-on-line not only yields a high inrush current, but also yields a high starting torque because the starting torque needs a high starting current to produce the moment of inertia applied to the rotor of the motor.

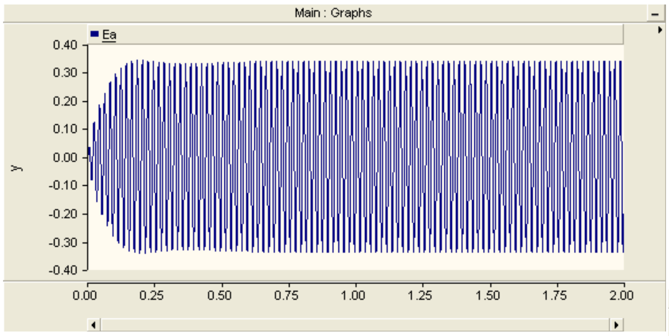

Fig. 11. Unbalanced Voltage in Direct-On-Line Starting

Fig. 11 shows the unbalanced voltage occurs during the starting of the induction motor by using the direct-on-line starting method. Obviously, the unbalanced voltage waveform occurs in the line voltage at terminal A of the induction motor. This phenomenon occurs because the dramatic high inrush current rises during the motor starting with a corresponding drop in the line voltage [5].

B. Simulation of Star-Delta Starting

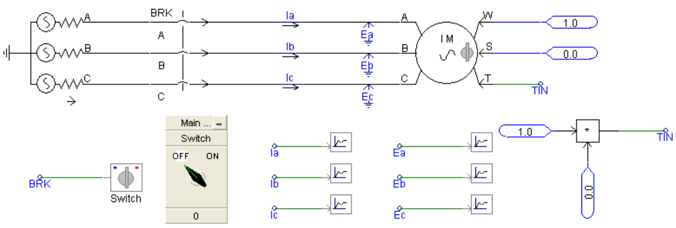

Fig. 12. Direct-On-Line Circuit Implementation by using PSCAD software

Fig. 12 shows the star-delta starting circuit implementation using Power Systems Computer Aided Design (PSCAD) software. The circuit operation of Power Systems Computer Aided Design (PSCAD) is the same as the real star-delta starting except for the contactor and thermal overload relay. The former are used as the controlling circuit of the switching process in real application while in terms of software simulation, the switching process is fully controlled by the control panel. The simulation circuit also yields the same results in the real starting process.

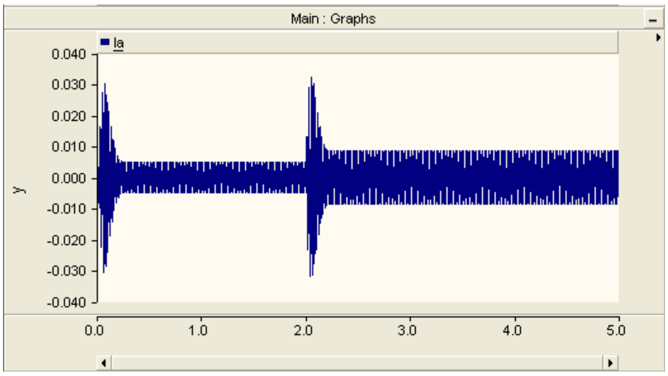

Fig. 13. Two times of Inrush Current during the Star-Delta Starting method

Fig. 13 shows the inrush current during the star-delta starting method. The first inrush current occurs during the starting of the induction motor. During the start-up, the rotor is in static condition as it draws more current to move the rotor and a severe inrush current can be observed. This is followed by the transition from the star to delta connection where the switching process causes the voltage breakdown even through a very fast period switching. The voltage breakdown also causes the inrush current.

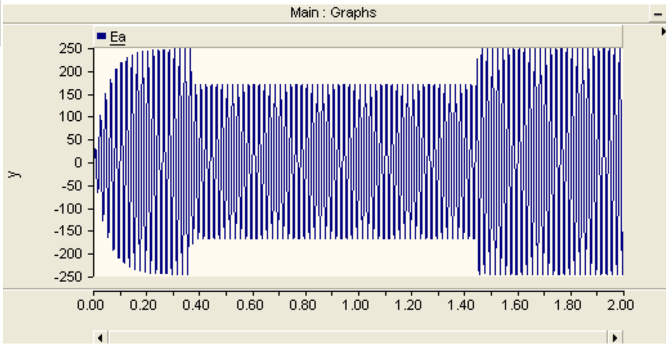

Fig. 14. Voltage Sag in the Induction Motor's Terminal A

Fig. 14 shows the voltage sag occurring at the terminal of the induction motor. The voltage sag exhibits the same characteristics as the real measured results conducted previously. This phenomenon occurs during the transition of the star connection to delta connection where the supply of 240V switches to 415V causing the voltage sag. Eventually, the current in the induction motor terminal will increase, causing a significant voltage drop in the motor's terminal.

C. Simulation of Autotransformer Starting

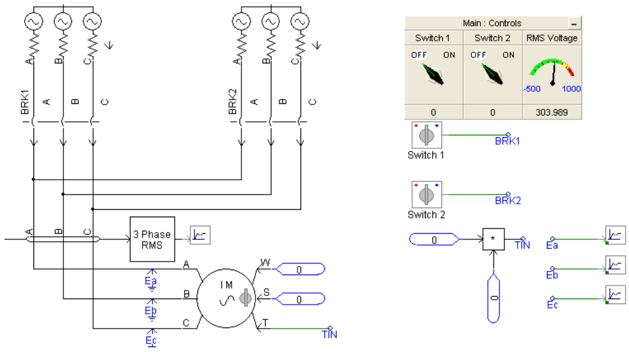

Fig. 15. Star-Delta Starting Circuit Implementation in PSCAD

Fig. 15 shows the model of the autotransformer in the Power Systems Computer Aided Design/Electromagnetic Transients including DC (PSCAD/EMTDC) simulation.

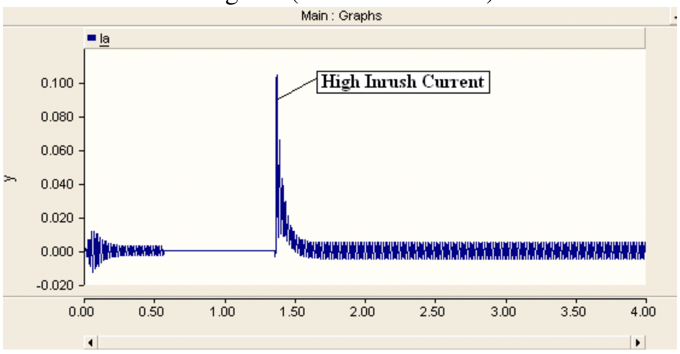

Fig. 16. Inrush Current in Autotransformer Starting

The inrush current as seen in Fig. 16 is caused by the voltage drop during the transition from 240V to 415V. The significant drop in the voltage corresponds to the high inrush current.

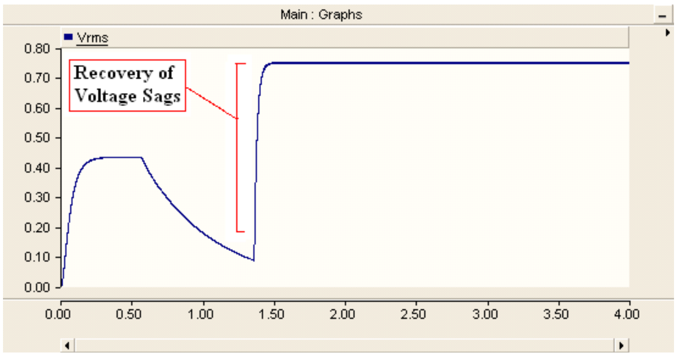

Fig. 17. Voltage Sags in Autotransformer

Fig. 17 shows the voltage sags in the autotransformer method. It can be seen that the severe drop at the starting in the V_{rms} during 415V.

VII. Conclusions

This paper presented practical and 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 problem compared with Direct-On-Line and Autotransformer starting motors. 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 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 the near future.

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