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Development of Pulse Modulator to conduct Life-Tests for Insulation Testing

[1] M.Balaji, [2] Joe Francis, [3] C.Praveenkumar
[1][2]UG Scholar, [3] Assistant Professor
Department of Electrical and Electronics Engineering
Sri Ramakrishna Engineering College
Coimbatore, Tamilnadu
[1] balajimohan48@gmail.com [2]jomonfrancis2@gmail.com [3] praveenkumar.chandran@srec.ac.in

Abstract: **The adoption of switching electronic converters for Adjustable Speed Drives (ASDs) can lead to some critical issues during operation. The presence of semiconductor switches like IGBTs and MOSFETs in Pulse Width Modulated (PWM) drives has increased the occurrence of steep fronted voltage surges (<500ns) in motors used as ASDs. Use of random wound motors as ASDs has aggravated the problem making it difficult to identify an impending interterm fault. This situation has necessitated the early identification of impending interterm faults to prevent the unexpected breakdown of critical drives. Due to the high switching frequencies as well as the high dV/dt in the output increased dielectric stresses are produced in the insulation system of the motor they supply. Due to the use of these solid state drives there have been concerns of premature failure in large, medium and high voltage motors.**

The paper deals with study that explores the effect of pulse duration and steepness on intercoil and interturn voltage distribution, with particular reference to random wound machines through simulation techniques. Interturn faults in such random wound motors can develop into earth faults in the coil crossing sections of overhang region. Predictions made on the insulation degradation using simulation waveforms will have the ability to forecast a possible impending insulation failure. Line end coil voltage waveforms show a little difference in their pattern when the interturn insulation is healthy and when the insulation resistance starts reaching the unsafe values.

Simulation is performed using both Unipolar and Bipolar pulses.

Keywords: **AFD drives, Motor insulation, Interturn faults, PWM Voltage.**

I. INTRODUCTION

The introduction of the first medium-voltage drive in 1983 ushered in a new era in the operation and control of Medium Voltage (MV) induction motors. These new drives quickly began to supersede devices such as gearboxes and eddy-current clutches, which had been previously used for these applications. In addition, rapid development of technology and manufacturing processes in the electronics industry has allowed for the development of semiconductor products, such as switches, with ever increasing current and voltage ratings. This in turn has allowed for the development of higher voltage solid state drives. Currently, solid state based medium voltage drives with operating voltages of 2.3 to 13.8kV are available on the market. As such, it is possible to increase the operating voltage; hence the power ratings of these drives continue to increase, while, keeping the current at a reasonable level, so as to keep the physical size of the components reasonable and allow for good thermal performance.

The new drives have applications in a diverse array of industries such as oil and gas, mining, metals, and marine sectors. Initially the first MV drives produced were used in lighter loads such as fans and compressors. As the technology further developed, higher power and voltage ratings were implemented in these solid state drives.

Many MV drives are designed and installed to run continuously. For example, in many oil and gas applications, where the drives are used for pumps and compressors, these installations must run continuously 24 hours a day, 365 days a year. Refineries operate continuously and any stoppages due to maintenance or equipment failure are costly.

To prevent these costly repairs and potential work stoppages motor manufacturers must continue to develop and improve the magnetic and insulation systems used in inverter duty motors. The newer solid state drives provide obvious advantages over the older methods of sped control. For example, they are much less prone to equipment breakdown, and offer significant energy savings over their mechanical alternatives for variable torque applications. For constant torque applications, while it has been shown that the energy savings are not significant enough to justify the capital cost of a solid state MV drive, there are other reasons which support the application of solid state MV drives. As mentioned previously, these reasons include increased reliability, as well as poor support available for legacy technologies.

A. *Types Of Medium Voltage Drives*

There are two main types of drives available in the market, Current Source Converters (CSCs) and Voltage Source Converters (VSCs). As the name implies, CSCs require a constant DC link current to operate. As a result, a reactor is required in between the line rectifier and the inverter, which for high power/torque applications can become quite large, and potentially increase the size of the drive greatly. CSCs offer the advantage of being more rugged and reliable compared to VSCs. For VSCs, a capacitor is required in the DC link to provide a constant DC voltage regardless of the load connected to the converter.

VSCs advantages over CSCs include better efficiency, superior transient response, lighter weight, lower price, and the flexibility of operating with either open loop (which is not possible with CSI) or closed loop control. As a result of these advantages, the majority of manufacturers utilize the VSCs topology in their designs. CSCs have been slowly squeezed out of the market by VSCs, leaving CSCs to be used solely in very high applications.

In the low voltage drive designs, the 2-level voltage source inverter topology has become the dominant configuration. This is mainly due to the fact that these products have been in use for quite a while, which allowed the technology to mature. Differentiation between manufactures is mainly based on smaller aspects like packaging, efficiency, and controller features as well as the improvement of the actual power semiconductors used in these drives. Currently, there is no dominant drive topology in the MV range. There are three main types of multi-level inverters: diode clamped, capacitor clamped, and cascade. The diode clamped inverter utilizes additional diodes to clamp the voltage exposed to the switches. One of the main advantages of the diode, and the capacitor clamped inverters, is that each switch is only exposed to a fraction of the DC-link voltage. The size of this fraction is dependent on the number of levels. The use of this topology allows for higher operating voltage compared to a 2-level inverter, when using switches with the same voltage rating. The cascade type inverter has a number of possible implementations. One method utilizes the series connection singe phase inverters, while another method utilizes the series connection of the three phase inverters.

The main advantage of multilevel inverters, from an insulation standpoint, is that they produce much more motor friendly waveforms as compared to a standard 2-level inverter. The multiple levels reduce the overall dV/dt in the output which occurs as the motor terminals, this in turn reduces the stress on the insulation.

Another advantage of multilevel converters is that because of their higher voltage outputs, due to the stacking of switching devices, the use of output transformers for large induction motor applications can be negated. While multilevel inverters have a number of obvious advantages they also have some weakness; the increased number of components required can reduce the overall reliability of the system as well the control algorithms required for multilevel converters are much more complex.

B. *Insulation Problem*

The application of solid state Pulse Width Modulation (PWM) drives for use with induction motors has created concerns with regards to the negative impact that these drives have on the insulation system of the motor. Most of the problems that occur due to the use of these drives result from the steep front pulses (high dV/dt) and added harmonic content of the output waveforms. These problems include large overshoots at the motor terminals, increased motor heating, and bearing currents.

The large overshoots that occur at the terminals result from using longer feeders to supply the motor. These overshoots occur because there is a mismatch between the cable impedance and the motor impedance. This mismatch causes the travelling wave produced by the inverter to be reflected back upon itself. The superposition of the reflected wave and the incoming wave can cause a spike of up to two times the nominal voltage to appear at the motor terminals. The increased motor heating is a result of the additional harmonic content found in the PWM waveform compared with that of a sinusoidal waveform. These harmonics do not contribute to the output power of the motor and are simply converted to heat, which may speed up the thermal degradation of the insulation. To combat the problem associated with these drives, there are currently two potential solutions, to either use an inverter duty motor to use a filter between the motor and the converter.

Often this inverter duty motor is simply a standard motor with improved cooling and added ground wall and turn-to-turn insulation. This solution has not completely eliminated the aging and degradation problems found in the insulation system. It has simply lengthened the aging and degradation problems before any serious problems or failures develop. Further increasing the insulation thickness is not an acceptable solution as it increases the size and cost of the motor. Instead of focusing on this type of solution motor manufacturers need to focus on developing and qualifying insulation systems that are much more resilient to the operating conditions produced by VFDs.

C. Induction Motor Insulation System

There are two types of stator windings used in the construction of induction motors namely; random wound and form wound coils. In addition, random wound stator coils are usually found in smaller induction motors with operating voltages of less than 1000V. Random wound coils are constructed using rounded copper conductors that are wound either by hand or by machine. The name random wound comes from the fact that the arrangement between turns is not exactly defined and can vary between coils of the same design. Form wound stator coils are mainly used in larger machines with operating voltages above 1000V. The construction and design of these coils is much more complex and involved, making them much more expensive than their random wound counterparts. Form wound coils are constructed using rectangular magnet wire, which is wound in a precise fashion to form the coil. These coils are then treated using global Vacuum-Pressure Impregnation (VPI). In the VPI process, the untreated coil is first placed in a vacuum chamber and dried for up to 8 hours. Then after vacuum treatment, the coil is immersed in a resin inside a pressurized tank. The resin under pressure is forced into the voids within the coil. Finally, the coil is removed from the tank and heated at a temperature of 120-150ºC to cure the resin.

II. DESIGN APPROACH BASED ON MODELING COMPUTATION

A. Design of Pulser Circuit in Unipolar and Bipolar Pulse

Due to high voltage operation and the need to test the suitability of individual components, a unipolar and bipolar pulser was designed. This allow the basic design to be tested on a smaller scale, to determine whether the selected components would be able to handle the voltages required by the modulator, and to determine the best way for connecting multiple switches in series. After which it could be use to test insulation system of inverter fed medium voltage induction motors. The topology of the pulse modulator is based on a simple single phase PWM inverter. Because this pulse modulator will primarily be used to test insulation samples, the device should attempt to accurately replicate the waveforms produced by MV PWM-VSC. One important constraints on this design is the fact that, the majority of power semiconductor products designed for high voltage operation and also designed with high current ratings.

For any surge, the motor winding presents itself like low-loss transmission line. The stator core would provide the return path for the surge current since the active conductors are insulated. Surges travel un-attenuated in the winding and get reflected at coil junctions at stator and overhang portions of a coil. Capacitive coupling between the turns overrides inductive between the turns at high frequencies.

B. Motor model

For a surge impinging on the motor winding, the winding presents itself like transmission line. Most of the motors have very low winding resistance, exhibiting essentially a low loss transmission line. Inter-turn capacitive coupling to earth overrides any mutual inductive couplings. The core might be represented as a magnetic member with a very low susceptance. The stator core would provide the return path for the surge current since the active conductors are insulated. Further the stator windings are either connected in delta or in star with insulated neutral. Hence for most part of the winding, the surges would travel without attenuation and also get reflected at coil junction at stator and overhang portions of a coil. The deviation from uniform theoretical transmission line model values due to actual construction can aggravate the situation. Such a deviation is very pronounced in stator windings using random windings. As far as the inter-turn coupling is concerned, for the high speeds of switching of igbts (typically <200ns), the inter-turn capacitive coupling can be safely assumed to be greater than inter-turn mutual inductive coupling.

C. Winding Model

Single layer mush winding; 24 slots; 416 turns/phase; slots/pole/phase; coil span of 5 slots; 4 coils/phase; 104 conductors per slot; conductor: bare diameter of 0.95 mm, insulated diameter of 1.041 mm and area of 0.709 mm^2 ; length of mean turn = 0.68 m; phase winding resistance at 75ºC = 8.37Ω (ρ = 0.021μΩ-m mm^{-2} at 20ºC).

Based on above data the machine winding with winding per phase was modeled as shown in Fig.1. The winding consisted of four coils in series. Windings of the next phases have been accordingly connected to show the effect of reflected waves at the remote end of the winding due to Δ and Y connections.

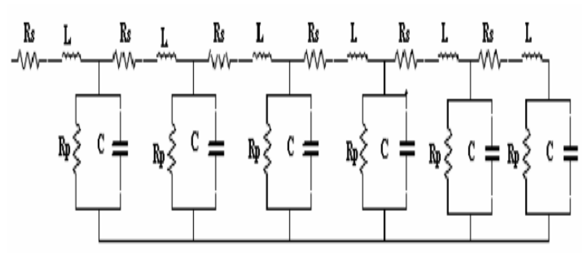


Fig.1 Winding Model

For the physical parameters of the motor winding, calculations yielded following coil parameters: Coil Resistance: Rs=2Ω; Inductance: L=85 μH; Earth Capacitance: C=100 pF; Winding Insulation Resistance: Rp=1GΩ.

Line-end coil model to study the inter-turn winding has been considered as a multi-conductor transmission line. For the inter-coil voltage distribution R, L, C values of the individual coils have been considered. However, for the study of inter-turn voltages the first three turns of the line end coil have been considered. This is based on the findings that the initial voltage distribution due to fast fronted surges in the line end coil is mostly decided by the first few turns. Also, the variance of earth capacitance in the overhang and slot regions have been considered for calculating inter-turn voltages.

D. Intercoil Voltage Distribution

Stator is connected in a delta connected mode, where the R-Phase is an impulse. Y-phase and B-Phase are connected in series across R-phase. The next end is grounded as shown in intercoil voltage distribution model. The Positive and negative polarity pulses in the interturn voltage distribution was negligible. In the case, the input is applied with a single square pulse and continuous pulses with polarity of 50% duty cycle. 50V peak voltage was given as an input and rise times used were 50 and 200ns.

E. Interturn Voltage Distribution

In intercoil voltage division, the initial voltage distribution is equal to the line end coil. The first three turns of the coil are used for line end coil model. Considered the conductors surrounded in the same slot act as shielding elements for the interaction of the flux generated by the other conductors in the same slot. Static capacitance value is considered due to the high frequency components, because the capacitance values are unaffected.

The inter-turn model assumed that in the slot region, 6 conductors placed on the periphery of the impulse conductors can totally shield the conductor from all other conductors and from the core. Capacitance of the conductor subtended on the encircling conductors was used for slot region and a dielectric permittivity of 2.5 was chosen. However, due to lose arrangement of the turns in the overhang where the effect of air overrides the enamel insulation, air permittivity was used. All the unit distance values were converted into real values, using the overhang and slot lengths of the conductors. The coil was divided into cable side of the overhang, slot region and the overhang in the rear of the machines. The line end coil model is shown in interturn voltage distribution model.

F. Values of Interturn Parameters

- Overhang parameters at the line end side: R1=6.4mΩ; L1=0.3μH; C1=30pF; Cg_1=20pF.
- Overhang parameters at rear side: R3=12.7mΩ; L3=0.6μH; C3=60pF; Cg_3=40pF.
- Slot portion parameters: R2=3.7mΩ; L2=0.2μH; C2=50pF; Cg_2=100pF.
- Insulation resistance: Rp=1GΩ; Earth Capacitance denoted by Cgk, k=1, 2, 3.

G. Test Circuit

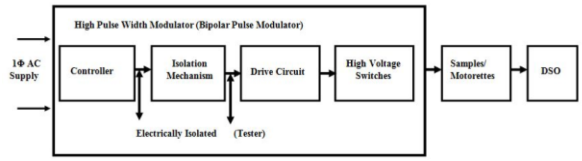


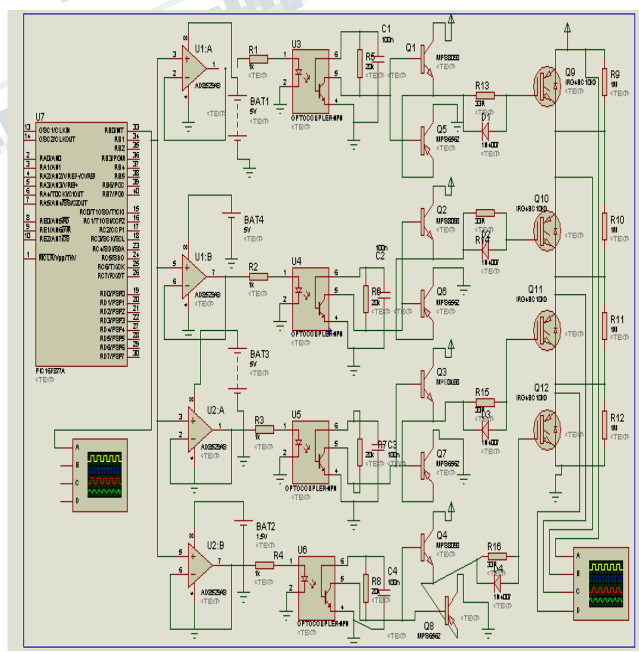
Fig.2 Block Diagram

The four main parts of the pulser are: the controller, the isolation mechanism, the drive circuit and the high voltage switches. The controller sends the gating signal through the isolation mechanism to the driver circuit, which then provides the current to properly drive the switches. This pulser was built in stages, starting with the controller and a single switch. This process was repeated until the pulser was operating with four switches in series to obtain the required voltage amplitude.

III. SIMULATION CIRCUIT AND OUTPUT WAVEFORM

The simulation was done using PROTEUS software. The circuit for both Unipolar and Bipolar with Interturn and Intercoil voltage generation is give below with their output waveforms.

A. Unipolar Driver Circuit & its Output Waveform



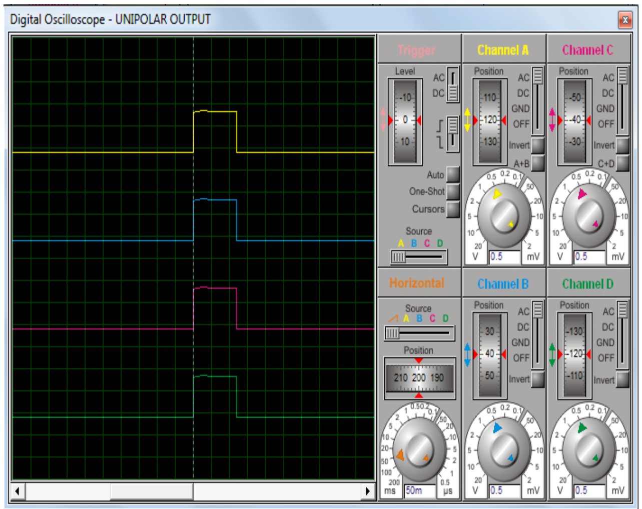


Fig.3 Unipolar Driver Circuit & Output Waveform

B. Bipolar Driver Circuit & its Output Waveform

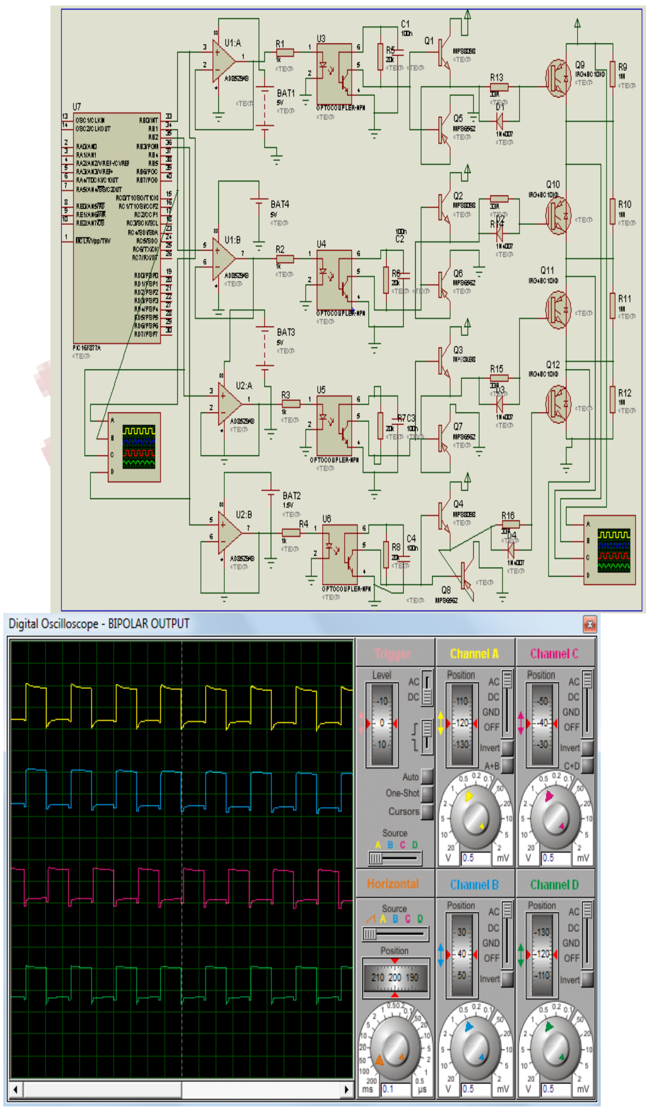


Fig 4: Bipolar Driver Circuit & Output waveform

C. Output Waveform of Intercoil and Interturn Voltage Distribution-Unipolar Pulse

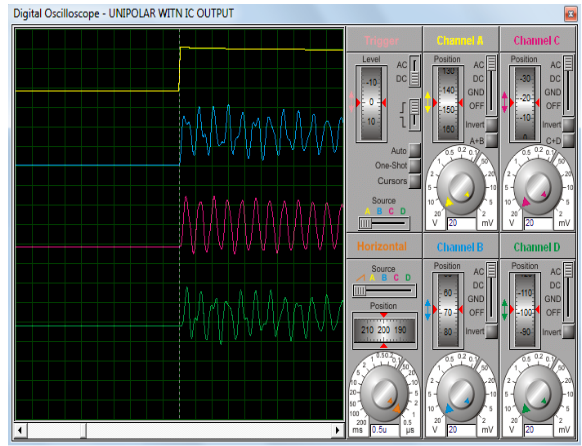


Fig.5 Intercoil Voltage Distribution-Unipolar Pulse

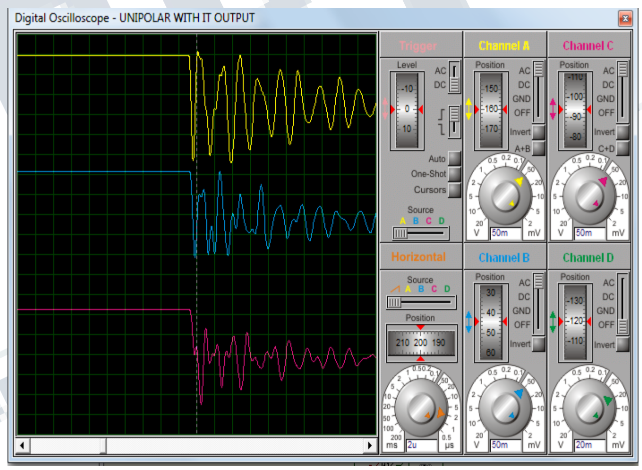


Fig.6 Interturn Voltage Distribution-Unipolar Pulse

D. Output Waveform of Intercoil and Interturn Voltage Distribution-Bipolar Pulse

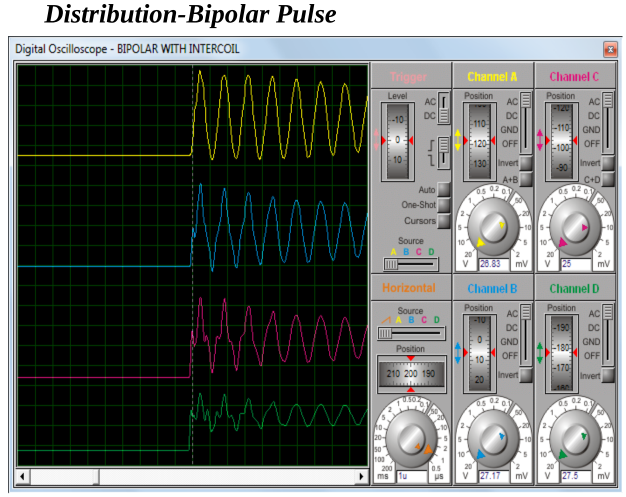


Fig.7 Intercoil Voltage Distribution-Bipolar Pulse

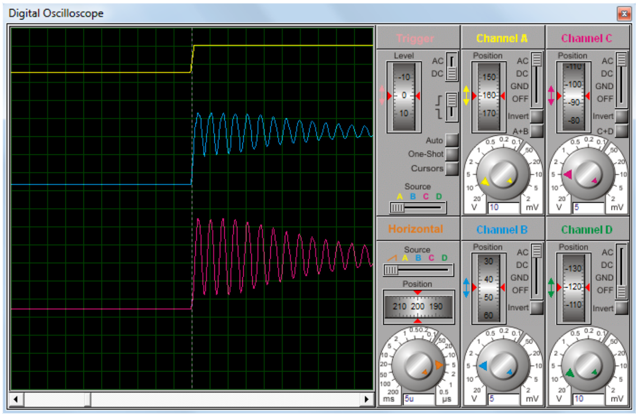


Fig.8 Interturn Voltage Distribution-Bipolar Pulse

IV. DISCUSSION ON RESULTS AND CONCLUSION

A. Discussion on Results

Winding model arrived at using; a motor with rating 2.2kW, 400V, 50Hz, 3Φ, 4-pole and Δ- connected induction motor for simulation. The effects of fast fronted waveforms on the model were studied through simulation using the software PROTEUS. Simulation pulses resembling the PWM pulses in ASDs were generated through microcontroller and their effect on intercoil and interturn voltage distribution were studied.

Simulation results show that:

- Voltage across line-end coil can reach up to 50% of incident surge for a 200ns rise time surge and up to 92% for a surge with 50ns rise time.
- The types of stator winding (either delta or star) modify the overvoltage magnitudes; with delta connection showing a higher coil-to-earth stress at star end.
- Interturn voltages can reach up to 80% of applied voltage for surges with 50ns rise time.

B. Conclusion

- Pulse rise times play a major role in the initial voltage distribution and pulse durations determine the final voltage distribution caused by internal winding surge reflections.
- Coil to earth voltages can reach dangerous magnitudes toward the winding end due to reflected waves inside the stator. These over voltages can easily become interturn voltages in the overhang region, causing premature insulation failures.

REFERENCES

[1] Boehne.E.W, (1930) 'Voltage Oscillations in Armature Winding under Lightning Impulses-I'. Trans. Am. I.E., pp: 1587-1615.

[2] Chapter 8.7 on Power Cables, Siemens Electrical Engineering Handbook, Wiley Eastern Limited. Fifth Reprint, 1993, pp:467-476

[3] Greg C.Stone, (January/February 2005) 'Recent Important Changes in IEEE Motor and Generator Winding Insulation Diagnostic Testing Standrads', IEEE Transactions on Industry Applications. vol.41, No.1, pp: 91-100.

[4] Guastavino.F and et.al (2005), 'Medium Term Aging Characterization of Enamelled Wires for High Frequency Applications', IEEE Transactions on Dielectrics and Electrical Insulation', vol.12, No.3, pp: 524-529.

[5] Mike Melfi and et.al, (July/August 1998) 'Effect of Surge Voltage Risetime on the Insulation of Low-Voltage Machines Fed by PWM Converters', IEEE Transactions on Industry Applications. vol.34, No.4, pp: 766-775.

[6] Ponnuswamy Rajkumar S. and Ebenezer Jeyakumar A., (2008) 'Stress Due to Transient Voltage Distribution in the Windings of Random Wound Motors Fed by PWM Converters', International Journal of Electrical and Power Engineering 2(5):327-332, Medwell Journal. ISSN: 1990-7958.

[7] Ponnuswamy Rajkumar S. and et al. (2011), 'Identification of Impending Interturn Faults in Random Wound Induction Motors used in Adjustable Speed Drives', WSEAS Transactions on Circuits and Systems, Issue 2, vol.10, pp: 59-68.

[8] Pravin Iyengar and et al. (2013), ' Design and Analysis of an Enhanced MOSFET Gate Driver for Pulsed Power Applications', IEEE Transactions on Dielectric and Electrical Insulation, vol.20, No.4, pp: 1136-1145.

[9] Sidney Bell and Jason Sung, (September/October 1997) 'Will Your Motor Insulation Survive a New Adjustable- Frequency Drive?', IEEE Transactions on Industry Applications. vol.33, No.5, pp: 1307-1311.

[10] Wright M.T., Yang S.J., Mcleay K., (1983) 'General theory of fast-fronted inter-turn voltage distribution in Electrical Machine windings'. IEE. Proceeding, Pt.B, 130(4): 245-256.

[11] Yuseph Montasser, (2006) 'Design and Development of a Power Modulator for Insulation Testing', M.Tech Thesis presented to the University of Waterloo, Ontario, Canada.