Investigation on Voltage Distribution in Motor Winding and its Effect When Supplied With PWM Converter

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Abstract: This paper present the investigation on transient over voltage that appears across the motor terminals when motor is supplied with a sinusoidal supply and with a PWM converter. When motor is operated on sinusoidal supply, then during switching period voltage across motor phase becomes equal to supply line voltage and the maximum voltage across any of the coil obtained is 30% more than the rated value. Unexpected behaviour was observed in variation of coil voltage (harmonic voltage after few cycle from starting) with sinusoidal supply during starting, however this is not producing large over voltages or high dv/dt. Voltage rise time when motor is supplied with converter is very small and is of the order of micro second. In some cases the peak voltage at motor terminals reaches to value which more than twice the value of dc link voltage and rated line to line voltage of the motor. The distribution of voltage during switching condition is not even among the coils of a winding and hence turns. The voltage drop in coils near the terminal is more than that of in other coils. The measured voltage drop across first coil from terminal of winding of four coils in series is varying 30 to 65.8% of the phase voltage against 25% of the phase voltage. Comparison of wave forms for sinusoidal supply and inverter supply shows that distortions were very large with inverter supply which increases the losses and produces more stresses on the insulations. This paper highlights the factors which affects the magnitude of over voltage its propagation in motor winding.

Key words:- Over voltage, AC machine, PWM converter, Turn insulation

I. INTRODUCTION

An important factor in industrial progress during the past five decades has been the increasing sophistication of factory automation which has improved productivity manifold. Manufacturing lines typically involve a variety of variable speed motor drives which serve to power conveyor belts, robot arms, overhead cranes, steel process lines, paper mills, and plastic and fiber processing lines to name only a few. Earlier all such applications required the use of a DC motor drive since AC motors were not capable of smoothly varying speed since they inherently operated synchronously or nearly synchronously with the frequency of electrical input. To a large extent, these applications are now serviced by what can be called general purpose AC drives. In general, such AC drives often feature a cost advantage over their DC counterparts and, in addition, offer lower maintenance, smaller motor size, and improved reliability. However, the control flexibility available with these drives is limited and their application is, in the main, restricted to fan, pump, and compressor types of applications where the speed need be regulated only roughly and where transient response and low-speed performance are not critical. Advances in solid state technology have overcome all these difficulties. Among the various techniques available for controlling the speed, the PULSE WIDTH MODULATION (PWM) technique is most widely used.

The advantages of a PWM converter using IGBT are so attractive that most of the drive manufacturers are uses it. This solution is applied to a wide range of power 0.1 kW up to some MW.

Prior to the introduction IGBT switching devices, the main issue motor designers were concerned with in mating a motor to an adjustable speed drive (ASD) was the increase in temperature rise from the harmonic losses the ASD introduced [1]. With the introduction of IGBT ASD, a second issue has become as important as the thermal issue—insulation integrity. The PWM inverter mode of control generates a large frequency spectrum. Without any extra filtering device, and in order to protect the environment from the electromagnetic disturbances caused by this mode of control, the motor can be fed through a screened cable. Nevertheless, this solution leads to undesired over voltages at the motor terminals and solicitates heavily the motor insulation much more than in a direct connection to the power supply network. Usual standards applied to the industrial induction motors recommend to keep the limit value of the voltage rise dv/dt <500V/µs for the motor in order not to reduce its life time. This value is suitable for a standard motor fed directly by the network power supply, but when the motor is fed by an inverter without any filtering device, the dv/dt may reach up to 7000 V/µs or even more depending on the installation. Therefore, for each case, it is very important to make sure that the insulation of the motor used will stand such a supply mode.

II. MOTOR – ASD SYSTEM

Figure 1 show the system studied. It consists of an induction motor fed by a PWM converter through a cable.

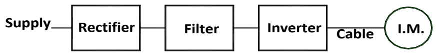


Figure 1 Motor Converter System

Rectifier is a diode bridge rectifier whereas the power elements used in the frequency are IGBT providing a fast commutating period of 200 ns. The PWM switching frequency

f_s of the inverter used in this installation can be set from 1 to 16 KHz.

III. THEORITICAL BACKGROWN

3.1 Determination of the transient over voltages and the voltage rise dv/dt at the motor terminals

The voltage waveform of a PWM control is shown in figure 2. It consists of various step functions.

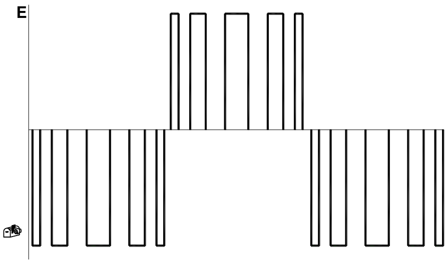


Figure 2 PWM waveform L-L applied voltage

When these rapid step-functions changes are applied to the cable or to the induction motor through a cable, considering zero initial charges on the cable, the transient overvoltages at the cable is given respectively by the following analytical expression (1). Figure 3 represent the circuit-diagrams of a cable supplied with step voltage V.

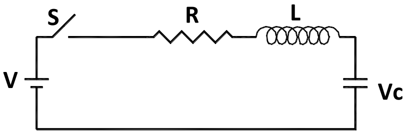


Figure 3 Circuit Diagram of the cable

$Vc(t) = V\,(1 - \cos(\omega t) * e^{-t/\tau})$ ______________(1)
Where
V = Supply Voltage,
$\tau = 2L/R$ Time constant,________________(2)
$f = \omega/(2\pi)$,

$$\omega = \sqrt{\left(\frac{1}{LC}\right) - \left(\frac{R}{2L}\right)^2} \text{ ___________(3)}$$

$L = L' * l$______________________________(4)
$C = C' * l$______________________________(5)
$R = R' * l$______________________________(6)
L’,C’ and R’ are being inductance, capacitance and resistance per unit length of cable and
l = Length of cable.
The rate of rise of voltage is given by equation

$$\frac{dVc(t)}{dt} = V\omega \sin\omega t * e^{-\frac{t}{\tau}} \text{ ____________(7)}$$

When motor is connected at the end of cable then the system equivalent circuit is as shown in figure 4. The voltage across the motor terminal is given by the equation 8.

$$vc(t) \cong V[1 + A * e^{-t/\tau_1} - B * \cos\omega t * e^{-t/\tau} \text{ _(8)}$$

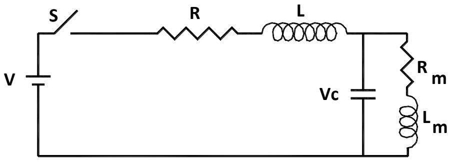


Figure 4 Circuit Diagram of the cable and the motor

τ_1 = time constant depending on the motor characteristics.

A, B are constants depending on the applied impulse voltage V, and the cable and the motor parameters.

3.2 Travelling-wave analysis

The voltage surges due to the fast switching of IGBT transistors cause electric wave propagation between inverter and motor. For an ideal cable with negligible losses, one has:

$$\frac{\partial^2 v}{\partial x^2} = L'C'\frac{\partial^2 v}{\partial t^2} \text{ ___(9)}$$

The characteristic impedance of the cable is given by

$$Z_c = \sqrt{\frac{L'}{C'}} \text{ ___(10)}$$

The solution of equation (9) is given by:

$$v(x,t) = vp(x - ct) + vr(x + ct) \text{ __(11)}$$

vp and *vr* represent respectively the forward and backward traveling waves.

$$c = \frac{1}{\sqrt{L'C'}}\ m/s \text{ ___(12)}$$

C is velocity of wave.

Different cases have to be considered.

- If the cable is open at the end, the voltage at the cable terminal is equal to twice the magnitude of the incident voltage
  $$v(l,t) = 2 * vp(l,t) \text{ ___(13)}$$
- If the cable is terminated by a resistance R, one has:
  $$v(l,t) = (1 + \rho_R)vp(l,t) \text{ ___(14)}$$

Where ρ_R is load reflection coefficient

$$\rho_R = \frac{R - Z_c}{R + Z_c} \text{ ___(15)}$$

- If the cable is terminated by a resistance R, which is equal to the characteristic impedance of the cable, the incident voltage will not be reflected. One obtains:

$$v(l,t) = vp(l,t)\_\_\_(16)$$

- If the cable is terminated by a capacitor C one has:

$$v(l,t) = 2 * V\left(1 - e^{-\frac{t}{\tau_1}}\right)\_\_\_(17)$$

Where

$$\tau_1 = CZ_c\_\_\_(18)$$

- If the cable is terminated by a capacitor C in series with a resistor one obtains:

$$v(l,t) = 2 * V\left(1 - \frac{Z_c}{R + Z_c}e^{-\frac{t}{\tau_2}}\right)\_\_\_(19)$$

Where

$$\tau_2 = C(R + Z_c)\_\_\_(20)$$

By considering R = Z_c, the transient overvoltage at the end of the cable is given by equation (21)

$$v(l,t) = V\left(2 - e^{-\frac{t}{\tau_3}}\right)\_\_\_(21)$$

Where

$$\tau_3 = 2CZ_c\_\_\_(22)$$

The termination impedance consisting of a combination of resistance and capacitance can be used as an efficient measure to reduce the transient overvoltage at the motor terminals. As discussed earlier that when motor surge impedance is high compared the cable characteristic impedance, the effect is a voltage doubling (test show even higher than doubling) on the leading edge of the voltage pulse at the motor [2]. On pulse width modulated ASDs, thousand of pulses per second are applied to the motor. The National Electrical Manufacturers Association (NEMA) recognized that these pulses could damage the motor insulation and has written into their standard NEMA MG1-31 that motor design for use on ASDs must be capable of operation in the presence of 1600 volt peak amplitude pulses with rise time of 0.1 microseconds or greater [3]. NEMA standard MG1-30 also defines the insulation capability of standard motors used on drives to be a much lower number-1000 volts peak with a 2 microsecond rise time [4].

Voltage rise time is a very important parameter in determining motor insulation system integrity. It determines voltage amplitude at the motor (in conjunction with the cable length between the motor and the ASD) and the voltage distribution on the individual motor coils.

It should be noted that voltage doubling did occur on ASDs prior to the introduction of IGBT switches. However, the previous technology switches (Gate turn off transistors and Bipolar junction transistors) had longer rise times resulting in voltage doubling occurring with longer cable lengths and more even voltage distribution in the motor windings. The net effect of these is that ASDs with IGBT switches have more severely stressed motor insulation.

IV. MOTOR WINDINGS: FORM COIL VS RANDOM

To understand the various ways motors are built to handle the higher voltage amplitude and voltage distribution differences an ASD introduces, it will be helpful to discuss form coil and random winding techniques.

Motor built for medium-voltage applications are rated for the system voltages to which they are applied. At medium voltages, motors are typically built with form coil windings. Form coil windings have insulated rectangular wire, and are carefully taped or wrapped and varnished to eliminate the presence of air so that partial discharge between wires is avoided. (Partial discharge is defined as the ionization of air leading to an electrical breakdown in a void of any geometry within insulation subjected to an electrical field) The nature of the construction assures that the turns are in sequential order. Therefore, Turn 1 would only touch Turn 2, Turn 2 would only touch Turn 1 and 3, etc. with this careful turn placement, the voltage between adjacent wires is limited to the turn to turn voltage.

Conversely, on low-voltage system-600 volts and below-motors are usually built with what is known in the industry as random windings. Random wound motors are wound with multiple strands of round magnet wire and are often wound on tooling (Known as farmo) to a specific shape, then inserted into the stator slots. During this wind/insert process, the adjacent wires could in the worst case have the first and the last turn touching (hence the term random winding). If the first and last turns are in contact within a coil, adjacent turn voltage can be full coil voltage, not sequential turn voltage. Additionally, on some types of random coil windings, the end turns of adjacent coils are not separated, so in the end, turns in adjacent coils can touch, resulting in adjacent wire voltage exceeding coil voltage.

Random windings are often vacuum pressure impregnated (VPI), dip, or flood varnished. This is done in an attempt to eliminate all air pockets between wires, replacing them with varnish. The numerous crossovers and wire interfaces combined with round wire geometry make it virtually impossible to eliminate all the air pockets. As stated above, these little air pockets makes partially discharges possible if an adequate voltage to start the partial discharge is present.

As can b seen, the two big differences between the form coil and random windings are:

- Adjacent wire voltage can be higher in the random winding, and

- Random windings are more likely to have air pockets between wires. (Air is a necessary ingredient for partial discharges.)

A lot of very interesting papers have been reported on motor over voltages [5, 6], however, this effect is still not sufficiently described.

V. EXPERIMENTATION

Two motor were design and manufactured with following rating:

1. Frame 71, 3-phase, 415 V, 300 W, 50 Hz, 2-Pole, Class F, Continuous duty Induction motor.
2. Frame 71, 3-phase, 415 V, 300 W, 50 Hz, 4-Pole, Class F, Continuous duty Induction motor.

Stator of first (2-pole) motor was wound as per detail given in diagram Figure 5. The number of turns per coil was 130. There were four coils in series per phase for all three phases. The terminal at the end of each coil is taken out for the purpose of measuring voltage. Accordingly each phase winding is having five terminals as shown in figure 7. The coils were made from dual coated hermetic grade super enameled copper wire of 27 swg. This wire is having fine covering of enamel.

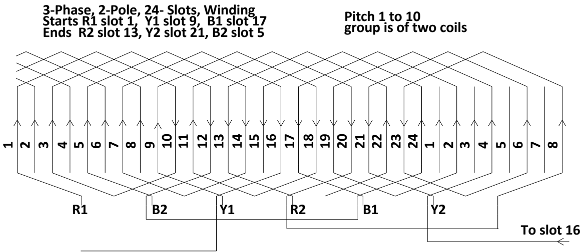


Figure 5

Stator of second (4-pole) motor was wound as per detail given in diagram Figure 6. The number of turns per coil was 130. There were four coils in series per phase for all three phases. The terminal at the end of each coil is taken out for the purpose of measuring voltage. Accordingly each phase winding is having five terminals as shown in figure 7. The coils were made from dual coated hermetic grade super enameled copper wire of 28 swg. This wire is having fine covering of enamel.

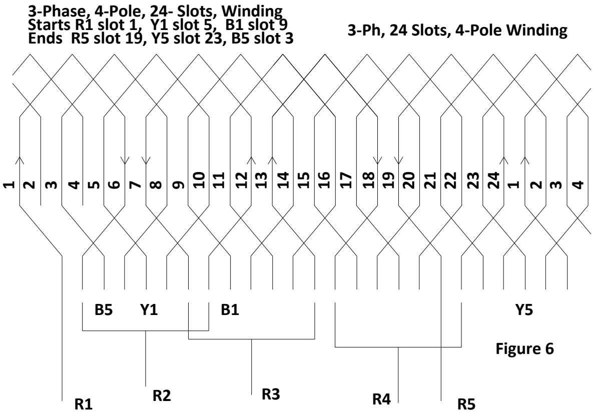


Figure 6

For understanding the voltage distribution in winding the voltages at different locations are measured as shown in figure 7.

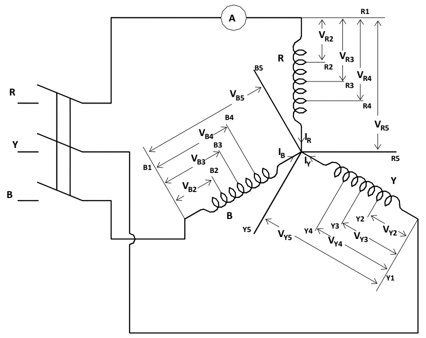
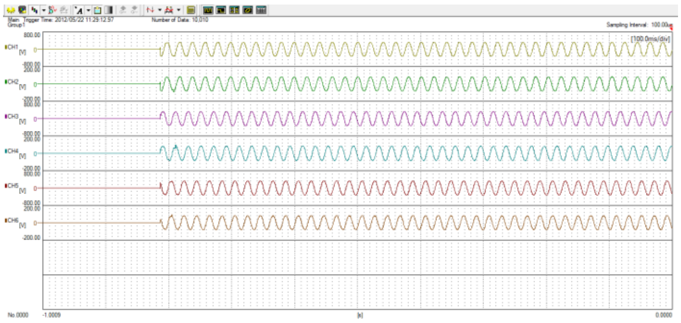


Fig. 7 Measurement of Voltage Wave form

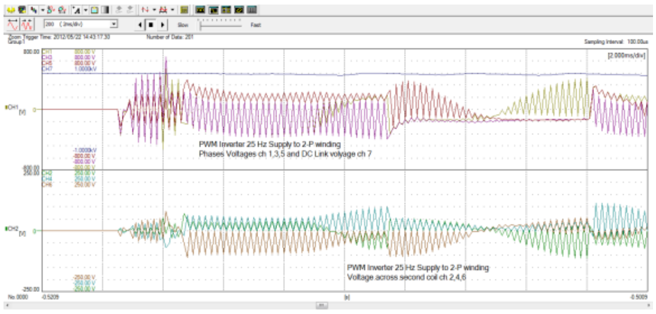
The voltage measurement set-up is shown figure 8.

Figure 8

Around 600 waveforms are recorded for different PWM frequencies varying from 20 Hz to 70 Hz and for 50 Hz utility supply. Sample waveforms are shown below.

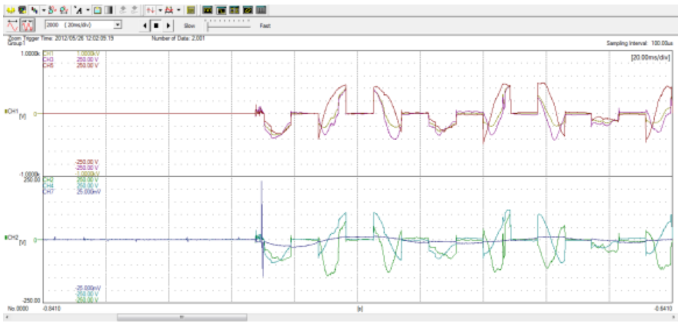


50 Hz, Utility supply, Wave form No. KRK0004,		
Phase	Item	First Peak
R-Phase	Phase Voltage	236.22 V
	Voltage first across coil	74.803 V
Y-Phase	Phase Voltage	181.10 V
	Voltage first across coil	43.307 V
B-Phase	Phase Voltage	251.97 V
	Voltage first across coil	58.433 V

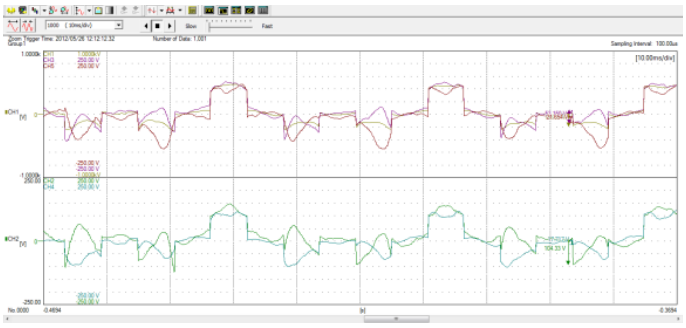


25 Hz, PWM converter supply, Wave form No. KRK0023, 2-P				
Phase	Point	1	2	3
	Item	Volts	Volts	Volts
R-Phase	Phase Voltage	1014.1	472.44	503.9
	Voltage second across coil	59.05	33.46	114.1
Y-Phase	Phase Voltage	900.79	459.84	478.7
	Voltage second across coil	78.74	69.05	98.42
B-Phase	Phase Voltage	459.84	94.48	541.7
	Voltage second across coil	108.27	90.55	102.8

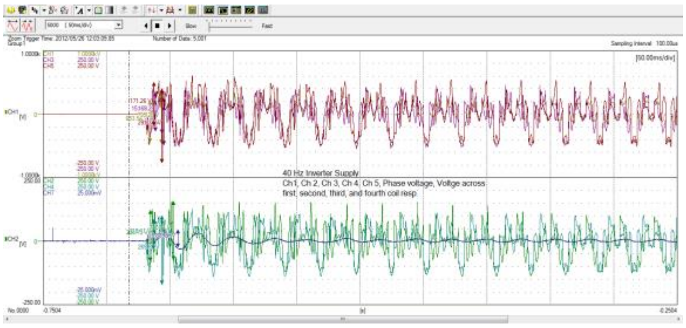
The wave forms for 20 Hz to 60 Hz are shown *below*.



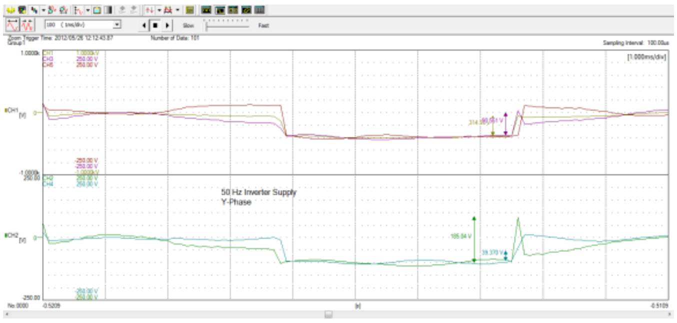
Phase	Item	Voltage Variation
R-Phase, 20 Hz KRK0106, 2-P	Phase Voltage V_{15}	429.43 V
	Voltage across first coil V_{12}	222.44 V
	Voltage across second coil V_{23}	137.80 V
	Voltage across third coil V_{34}	59.05 V
	Voltage across four coil V_{45}	9.84 V



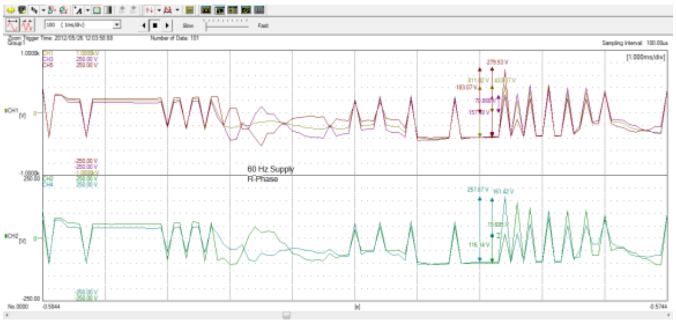
Phase	Item	Voltage Variation
Y-Phase-30 Hz KRK0122, 2-P	Phase Voltage V_{15}	196.85
	Voltage across first coil V_{12}	104.33
	Voltage across second coil V_{23}	53.15
	Voltage across third coil V_{34}	17.71
	Voltage across four coil V_{45}	21.66



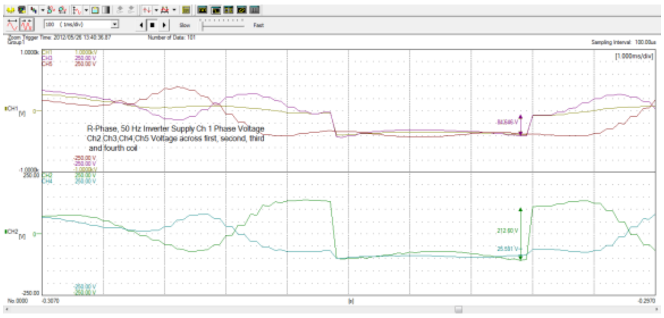
Phase	Item	Voltage Variation
R-Phase, 40 Hz KRK0108, 2-P	Phase Voltage V_{15}	251.97
	Voltage across first coil V_{12}	179.13
	Voltage across second coil V_{23}	78.74
	Voltage across third coil V_{34}	21.65
	Voltage across four coil V_{45}	-27.55



Phase	Item	Voltage Variation
Y-Phase, 50 Hz KRK 0124, 2-P	Phase Voltage V_{15}	314.96
	Voltage V_{12}	185.04
	Voltage across second coil V_{23}	90.55
	Voltage across third coil V_{34}	39.37
	Voltage across four coil V_{45}	0.0



Phase	Item	Voltage variation
R-Phase, 60 Hz KRK0110, 2-P	Phase Voltage V_{15}	433.07
	Voltage across first coil V_{12}	17.71
	Voltage across second coil V_{23}	70.86
	Voltage across third coil V_{34}	161.42
	Voltage across four coil V_{45}	183.07



Phase	Item	Voltage Variation
R-Phase, 50 Hz KRK0139, 4-P	Phase Voltage V_{15}	322.83 V
	Voltage across first coil V_{12}	212.60
	Voltage across second coil V_{23}	84.64
	Voltage across third coil V_{34}	25.59
	Voltage across four coil V_{45}	0.0

VI. CONCLUSION

With utility supply the voltage is nearly equally distributed among all the coils of a phase connected in series. When motor is supplied with a PWM converter in certain situation the voltage appearing across the motor terminals is more than the rated value and this may be double than the rated voltage of the winding. This momentarily produces more stresses on the phase insulation. With PWM supply voltage is not getting evenly distributed among all the coils of a phase connected in series. The voltage across the coil near to the terminals is always more than the other coils. Sometimes this voltage is as high as 65.8% of the total voltage. Hence enhance insulation is required for the coil which is nearer to the terminal. The voltage distribution is independent of the number of poles of the winding.

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