Design of Filters to Reduce Transient Over voltages of Induction Motor Fed By Variable Frequency Drives

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Abstract: *The overvoltage at motor terminals fed by variable frequency drives produces severe stress on motor insulation systems. The paper aims to provide a comparative survey of existing filters designed to suppress overvoltage. These filters are passive and installed at both the motor and inverter terminals. The overvoltage is typically caused by the high change rate of the inverter output voltage* (dv/dt) *and the surge impedance mismatch between the inverter and the power cable of the motor. The paper discusses the design methodologies employed for these passive filters. This could include how the filters are constructed and tuned to address overvoltage issues. This paper presents a comparative survey of the existing filters of overvoltage suppression, which are passive filters at both motor and inverter terminals. The article also evaluates the practical applicability of these passive filters. This could include cost, ease of installation, and maintenance requirements. The design methodologies, effectiveness, and practical relevance of these passive filters are discussed through computer simulations based on MATLAB, and promising approaches are recommended for researchers and industrial users.*

Index Terms-: Variable Frequency Drivers, Induction Motor, Switch loss, Transients, Cable, Filter design

I. INTRODUCTION

To get the power signal near sinusoidal power switching devices, the increasing speeds of switching and related switching frequencies, in addition to the associated high-frequency operation of PWM AC drives. However, the consequent high rate of voltage rise, dv/dt, has adverse effects on motor insulation systems and contributes to bearing current problems [1][2][3]–[4]. Moreover, in some industrial applications, constraints are such that the motor and the PWM inverter have to be placed at separate locations. Thus, long interconnecting cables are often required between them. As presented in [1], narrow PWM pulses traveling on long wires from the inverter to the motor behave like traveling waves on transmission lines, in which a phenomenon of voltage reflection and possibly successive voltage reflection leading to overvoltage at the motor terminals will occur. The associated voltage reflection is a function of the inverter output pulse rise time and the length of the motor cables, as well as the surge impedances of the motor and cable systems [3], [4. In this case, if no mitigation measures are implemented, the motor would likely suffer from severe insulation damage, leading ultimately to failure. Additionally, NEMA has suggested that (dv/dt) be limited to less than $500V/\mu s$ For general-purpose motors in the 460V class [6]. Accordingly, this paper presents an effect on the reduction of overvoltage caused by high (dv/dt) switching and surge impedance mismatch in PWM variable frequency AC drives. The paper aims to identify and propose a suitable filter solution to reduce transients to protect the motor's insulation. This clarification further emphasizes the importance of addressing overvoltage issues caused by transients in motor systems powered by variable frequency drives (VFDs). By reducing these transients, the paper aims to enhance the insulation's durability and overall motor performance.

2. Analysis of the cause of over voltages:

An analysis of the causes of overvoltages in motor systems powered by variable frequency drives (VFDs) typically involves examining various factors contributing to this phenomenon. Here's an overview of the fundamental causes and factors often considered in such analyses:

Inverter Output Characteristics:

a. *dv/dt rate of voltage change:* One of the primary causes of overvoltage is the rapid change in voltage (dv/dt) generated by the VFD during switching. High dv/dt can induce voltage spikes and overshoots.
b. *Impedance Mismatch:*
   Surge Impedance Mismatch: When the surge impedance of the power cable connecting the VFD to the motor doesn't match that of the VFD or the motor, it can lead to reflections and overvoltage.
c. *Motor Characteristics:*
   The inherent inductance and capacitance of the motor windings can interact with the VFD output and contribute to overvoltages.
d. *Switching and Frequency:*
   The frequency at which the VFD switches can impact the magnitude of overvoltage. Higher switching frequencies may lead to higher dv/dt and overvoltage.
e. *Cable length and Quality:*
   Longer cables can introduce additional inductance and capacitance, affecting the cable's impedance and potentially leading to overvoltage. The cable quality used for power transmission can influence its ability to handle transients and overvoltage.
f. *Grounding and Shielding:*
   Poor grounding practices or improper shielding can exacerbate overvoltage problems.
g. *Load Variations:*
   Rapid changes in load conditions on the motor can create voltage transients.
h. *Protection and Control Security:*
   Insufficient or ineffective voltage protection mechanisms in the VFD can fail to limit overvoltage conditions.
i. *Control Strategies:*
   Poor control strategies in the VFD can lead to overshooting voltage levels during acceleration or deceleration.
j. *Environmental Factors:*
   EMI from nearby equipment or electrical disturbances can induce overvoltages. Malfunctions within the VFD, such as IGBT failures, can lead to overvoltage conditions.

Analyzing the causes of overvoltages is crucial for designing effective mitigation strategies. Engineers often employ impedance matching techniques, passive filters, and tuning the VFD control parameters to minimize overvoltage problems. Furthermore, simulations and testing can help evaluate and validate these strategies before implementing them in practical motor systems.

Transient Overvoltages at motor terminals fed by variable frequency drives are generated by three main aspects: the rise time of the PWM pulses, the cable length, and the impedance mismatch between the inverter, power cable, and motor. Most often, the cable length interconnecting the power converter and the specific layout of an industry installation dictates the motor. Therefore, we may have no choice in this matter. Thus, we can mitigate or compensate for the impedance mismatch and the rise time of the inverter output pulses, which determine two categories of mitigation methods for overvoltage in long-cable-fed vector-controlled PWM AC drives.

3. Voltage doubling effect :

The voltage doubling effect is noteworthy in electronics, particularly in circuits designed to produce higher voltages from lower input voltages. It relies on the principles of electronic components, such as diodes and capacitors, to generate an output voltage of approximately twice the input voltage's amplitude. This phenomenon is utilized in various applications, including voltage multipliers and power supply circuits, where higher voltages are required from a lower voltage source. The voltage doubling effect is a fascinating electrical phenomenon that allows for generating higher voltages from lower input voltages through diodes and capacitors. It plays a significant role in various electronic applications and is an essential concept in electronics and electrical engineering. Voltage doubling effect is similar to traveling waves in the transmission lines.

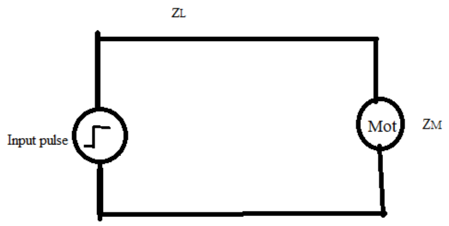

Fig:1 voltage doubling effect

$$\frac{v^{-}\left(t+\frac{z}{v}\right)}{v^{+}\left(t-\frac{z}{v}\right)}=\frac{Zl-Zc}{Zl+Zc}---(1)$$

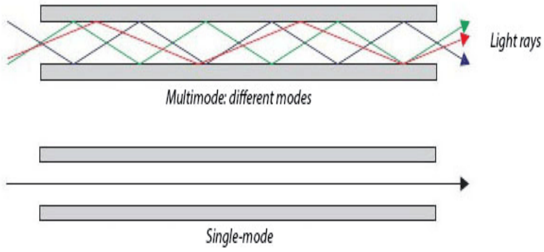

Fig:2. Multiple reflections in the cable

$$\Gamma_{\mathrm{M}}=\frac{\mathrm{z_m-z_c}}{\mathrm{z_m+z_c}} \text{ -----------------------(2)}$$

$$\Gamma_{\mathrm{S}}=\frac{\mathrm{z_s-z_c}}{\mathrm{z_s+z_c}} \text{ -------------(3)}$$

where, $\mathrm{Z_m}$ is the motor surge impedance, $\mathrm{Z_s}$, is the surge impedance of the voltage source inverter (typically $\mathrm{Z_s} \approx 0$), and $\mathrm{Z_c}$ is the cable surge impedance given by [3]:

$$\mathrm{Z_c}=\sqrt{\frac{\mathrm{L_c}}{\mathrm{c_c}}} \text{ ---------(4)}$$

where, $\mathrm{L_c}$, is the cable inductance per unit length, and $\mathrm{C_c}$, is the cable capacitance per unit length. Generally, if $\mathrm{Z_s} \approx 0$ it follows that, $\Gamma_{\mathrm{s}} \approx -1$, and the overvoltage magnitude is primarily determined by reflective co-efficientΓ_{M}.

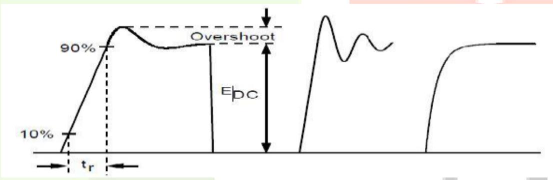

Fig 3: Pulse with various rise time

According to wave theory through cables and voltage reflection analysis, a propagation delay from the inverter output to the motor terminals can be expressed as

$$t_p=\frac{l_c}{v_p} \text{ ----------(5)}$$

where l_c is the cable length and v_p is the pulse propagation velocity in the motor cable and is given by [2]

$$v_p=\frac{1}{\sqrt{L_c C_c}}---(6)$$

The reflective coefficient is around 0.8 to 0.9 for the machines ratings less than 25 H.P.for a 4-core cable with a length of 100meters

$$v_p=\frac{1}{\sqrt{L_c C_c}}=\frac{1}{\sqrt{033\times10^{-6}\times180\times10^{-12}}} \quad (7)$$

$$=1.25\times10^{8} m/s$$

Filter Design:

The PWM inverter drive has a large dv/dt. The filter reduces the standard mode voltage, and the average mode current is also reduced.

Inductor:

The inductance used is around 5% of its base value. This inductor reduces current ripples; hence, the flux ripples also reduce. The power loss in this is high.

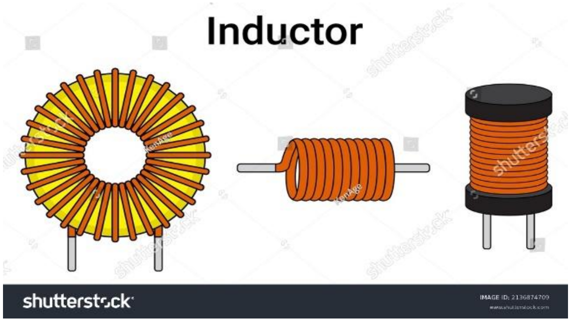

Fig 4: Basic structure of Inductor

1)Simple to use
2)High cost
3) Inefficient filtering

Sine filter:

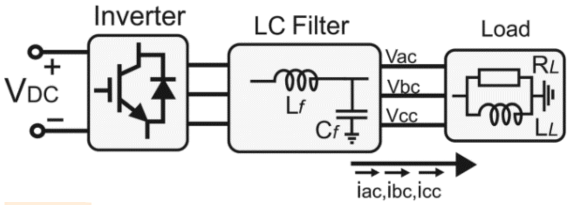

Fig 5: LC sine filter

The resonant frequency $w_r = \frac{1}{\sqrt{lfcf}}$ The LC filter is between a lower switching frequency and a higher fundamental frequency. Harmonics generated by the PWM inverter are not amplified and can dampen the oscillations. Voltage below the resonant frequency does not attenuate. Voltage above the resonance frequency attenuates.

4. LC resonant clamped filter(dv/dt):

The DC bus voltage and the load voltage ratings are fixed as per the requirement of the application. The critical design variables are resonant frequency I_{res}, resonant current ires, and rise time t_{rise}. The required rise time t_{rise} should be greater than propagation time t_p to avoid the voltage doubling at motor terminals.

$$\mathbf{t_{rise} = kt_p \qquad K>1}$$

It changes the slope of the voltage pulse, thereby increasing the rise time of the voltage. The resonance frequency is above the switching frequency of the inverter of the PWM inverter. This results in a small value of inductance and capacitance.

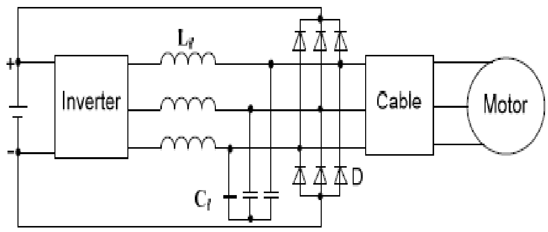

Fig 6: dv/dt Clamped filter

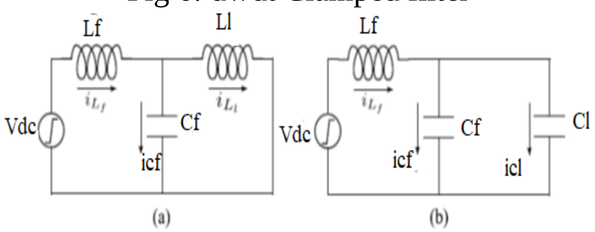

Fig 7: (a) Filter with induction motor leakage inductance (b) High-frequency model of filter

$$Lf(p.u) = Vdc(p.u)\{\frac{1}{(ires(p.u)\max Wrse(p.u)}\}$$

$$\{\frac{2\pi Vdc2\,(p.u)}{(ires)\max(\frac{dv}{dt})\max(p.u)}\} \text{-----}(8)$$

$$Cf(p.u) = \frac{1}{W2rse\,Lf(p.u)} \text{-----------}(9)$$

RLC filter:

A straightforward method to eliminate the motor terminal overvoltage is to use an impedance-matching circuit at the motor terminals. The terminator may be an RC or LCR circuit. The impedance of the parallel connection of the termination circuit and the motor impedance match that of the cable. As previously mentioned, the motor transient impedance is significantly higher than the cable impedance, which allows the motor impedance to be neglected in the circuit design. The terminator does not limit the d*u*/d*t*, but a correctly dimensioned terminator eliminates the overvoltage.

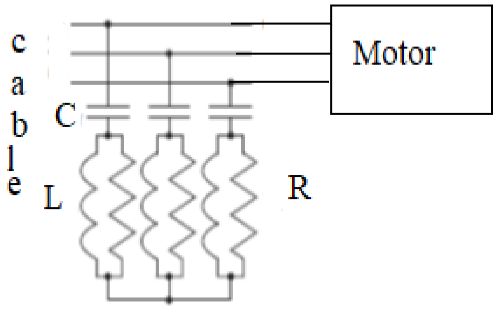

Fig-8: RLC impedance matching filter

The second-order filter is proposed to reduce the overvoltage at the motor terminals. The proposed second-order shunt filer is shown in Fig above. To minimize the overvoltage at the motor's terminals, the filter component values are selected such that the equivalent impedance of the filter closely matches the surge impedance of the cable.

$$Zeq=\frac{jRfWfLf}{Rf+jWfLf}-\frac{j}{WfCf} \text{ ------------(10)}$$

$$=\frac{\text{jwRfLf(Rf−jwLf)}}{(Rf+jwLf)(Rf-jWLf)}-\frac{j}{WfCf}\text{-----------(11)}$$

The Resistor Rf is designed to result in a damped circuit, as given by

$$Rf<\frac{\sqrt{LfCf}}{2Cf}\text{--------------------(12)}$$

The surge impedance parameters are given per unit length. So Z_0 will be constant for a given cable type. Therefore, the filter design will be the same for a provided cable regardless of the distance.

The resonant frequency of the filter was five times the PWM inverter's switching frequency. The filter's operating frequency to minimize the overshoot was chosen to be near the resonant frequency of the filter.

The LCR filter design at the motor

$$R=|Zsurge\ cable|\text{------(13)}$$

$$e^{(-wn*Trise)(1+Wn*Trise)}=0.9\text{-------(14)}$$

$$\frac{1}{RfCf}=2Wn\text{ ---------------(15)}$$

$$Wn^2=\frac{1}{LfCf}\text{-------------(16)}$$

- Understand the motor's specifications, the nature of transient voltage events, and the acceptable voltage limits.
- Choose an appropriate filter configuration (e.g., LC filter) based on the frequency range of the transient voltages.
- Calculate the values of the inductor (L) and capacitor (C) required to achieve the desired filter characteristics, such as cut-off frequency and impedance matching.
- Select commercially available components (inductors and capacitors) that meet the calculated values and voltage/current ratings.

5. Result & Analysis

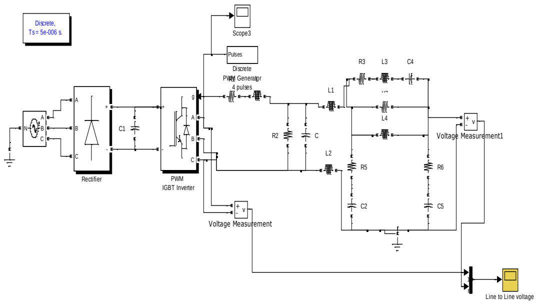

Fig-9: Matlab simulation without filter

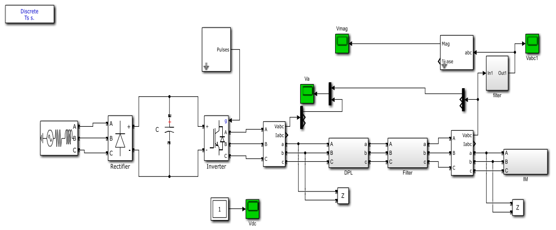

Fig: 10: Matlab simulation with filter

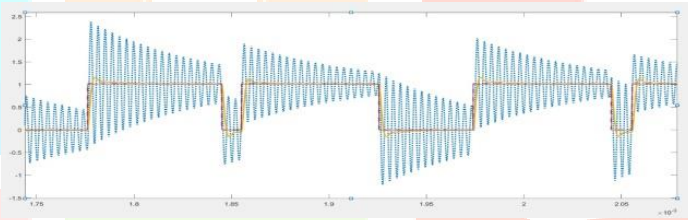

Fig:11: Comparison of transient voltages at the motor terminals

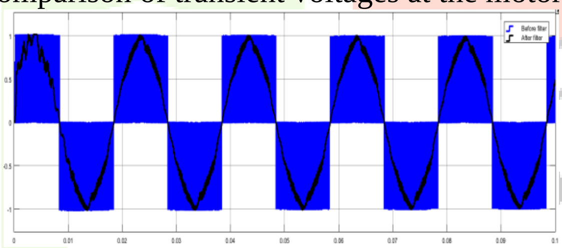

Fig:12: Sinusoidal out from inverter

6. Conclusions:

From the above figures, It is observed that figures or data that transient voltages are occurring at the motor terminals when no filter is employed. Transient voltages typically refer to abrupt or temporary fluctuations in voltage levels that can be detrimental to the motor's operation and insulation. To address the issue of transient voltage, a dv/dt filter is used at the terminals of the inverter. This filter is designed to increase the rise time of the voltage pulses produced by the inverter. By doing so, it aims to reduce the rapid rate of voltage change (dv/dt), a common cause of transient voltage spikes. The conclusion drawn from the study or analysis is that the combination of the dv/dt filter at the inverter terminals and the RLC double-tuned filter at the motor terminals positively reduces the impact of transient voltage. In other words, these filters effectively mitigate the overvoltage and temporary voltage issues observed when no filter is used. The study suggests that by implementing both a dv/dt filter at the inverter terminals and an RLC double-tuned filter at the motor terminals, transient voltages and their associated adverse effects on the motor can be significantly reduced. These filters work in tandem to improve the quality and stability of the voltage supplied to the motor, thus safeguarding its operation and insulation.

It is concluded that transient voltages occur at the motor terminals without a filter. Still, with dv/dt and RLC double-tuned filter, the effect of transient voltage will reduce. dv/dt filter is used at the terminals of the inverter, which increases the pulse's rise time, and the RLC filter is used, which does the impedance mismatch at the terminals of the induction motor.

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