Abstract—Thyristors of press pack package is a widely used switch in high voltage pulse power applications. Thyristors are to be properly mounted to meet the datasheet specifications. Improper mounting results into higher electrical and thermal resistances and also adversely affects its surge current capability. Mounting method becomes important in application like crowbar where it demands high surge current and high di/dt ratings. This becomes more critical when thyristors are series connected. Hence in application like crowbar using the pre-calibrated mounting clamps available in the market without evaluation is inappropriate. This paper addresses the design method for the fabrication of mounting clamps for press pack package and analyses the torque-force relationship for a non-metallic bolt. The paper also details the procedure adopted for the evaluation of the mounting clamps to ensure it meets the desired tolerance levels. Based on the formulated design method compact mounting clamps for 10kV, 1kA crowbar are fabricated. Experimental results on a mounting clamp confirm the theoretical analysis.

Keywords—crowbar, mounting clamps, press pack package, nut factor, mounting force.

I. INTRODUCTION

In recent years, thyristors are used in many switching applications especially in the area of high voltage and high power. Static transfer switch, high power phase controlled rectifiers, crowbar and traction are some of the applications where thyristors are inevitable. In these applications thyristors are used due to its higher voltage and current ratings, compared to other semiconductor devices. Still in many of these applications to meet the required voltage and current ratings, thyristors are connected in series or parallel or both. Crowbar is a fault energy-diverting element [1] [2] built with series connected thyristors, connected at the output of high voltage dc source as shown in Fig. 1. The dc source will be feeding power to sensitive loads, like microwave or plasma tubes. All series connected thyristors are turned-on when fault signal receives from fault sensing elements, diverting the fault energy through crowbar in few microseconds. When crowbar is turned-on, the dc capacitor will discharge through the crowbar with high di/dt and high peak current, followed by a follow through current of lower magnitude until the input circuit breaker opens. Hence the thyristors used in crowbar application should have higher surge current and di/dt ratings.

Based on the packages available in the market, thyristors are classified as (a) Module type (b) Stud mount type and (c) press pack type.

a) Module type: Here the silicon wafers are placed on an electrically isolated metallic base plate and then covered using a plastic enclosure as shown in Fig. 2(a). The heat transfer will be taken place through the metallic base plate which will be mounted on a heatsink.

b) Stud mount type: Here the anode will be of threaded bolt used to mount on a heatsink and the cathode is of thick metal cable, shown in Fig. 2(b), used to connect thyristor to the remaining circuit. Here heat transfer take place primarily through the threaded bolt side of the thyristor.

c) Press pack type: This package is also known by different names such as hockey puck, flat pack, disc and capsule shown in Fig. 2(c). Here both anode and cathode have a flat circular metallic plate, called pole faces, allowing the passage of current and provides double side cooling by mounting heatsink on both sides. Hence these type of thyristor gives excellent cooling and can handle higher power. Availability of this package at higher voltage and current rating along with higher surge current capability suits its use in high pulse power applications like in crowbar.

In all these packages proper mounting methods should be followed to meet the specifications mentioned in the datasheet [3]. Improper mounting will result into higher electrical and thermal resistances. The mounting methods requires close attention in application like crowbar, where current

Fig. 1. Power supply with dc capacitor ($C_{dc}$) and crowbar with voltage and current measurement points.

Fig. 2. Thyristor (a) Module type (b) Study type (c) press pack type.

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Subhash Joshi T. G. is with Development of Advanced Computing (C-DAC), Trivandrum, Kerala, India e-mail: (subhashj@cdac.in).

Vinod John is with Indian Institute of Science, Bangalore e-mail: (vjohn@ee.iisc.ernet.in).
reaches the surge current rating in short time demanding high $\text{d}i/\text{d}t$ requirements. The situation becomes more critical when press pack thyristors are connected in series due to accumulation of geometric tolerances. Hence in similar applications using pre-calibrated mounting clamps available in market without evaluation is inappropriate.

The pieces of information about various components of mounting clamp explained in different context are available in literatures [3]–[14]. In this paper a systematic method is formulated for the fabrication of mounting clamps for press pack package starting from the specification. It also details the method to establish the torque-force relationship especially needed when the bolts are fabricated with non-metallic material. The design method is experimentally verified and the mounting clamps are fabricated for $10\text{kV}$, $1\text{kA}$ crowbar application which is tested for its specified voltage and current rating. Experimental results confirm theoretical analysis.

II. MOUNTING OF PRESS PACK PACKAGE

In this package, silicon wafers are floating between the pole faces. While tightening the clamp pole faces will squeeze and makes contact with the silicon wafer [15]. The required amount of squeezing is specified in the datasheet as mounting force [16]. Since electrical current flows from one mounting surface to the other through the pole faces, the mechanical arrangement is not only to dissipate heat energy but also to conduct electrical current. The points of concern related to the mounting of press pack package are:

a) Uniform force distribution: It is important that the force appearing on the pole faces should be uniformly distributed over the entire surface. Otherwise, it leads to local mechanical stress on the silicon wafer and subsequently degrades its performance [17]. It also results in uneven electrical resistance which leads to severe local heating, increase in on-state voltage and adversely affect its surge current as well as thermal cycling capability.

b) Surface condition: Two parameters of interest are (a) flatness defined as measure of the net variation of surface and (b) roughness defined as a measure of micro-structure of the surface [4]. In most of the applications flatness and roughness should be kept less than $10\mu\text{m}$ [18]. If a good flatness and roughness are not maintained the area of contact will be incomplete and this results in local heating.

c) Maintaining force for longer period: Using belleville washers along with the nut helps in maintaining the set value of force for a longer period of time [19].

Higher clamping force will damage silicon wafer. Estimating the force directly with mechanical tightening tools are not feasible. But if the torque at which mounting bolt to be tightened to achieve the required force can be estimated then the torque wrench can be used to estimate the force.

III. ESTIMATION OF TORQUE FOR THE REQUIRED FORCE

The applied force on the pole face of the thyristor can be measured by using load cell placed in between the mounting clamp and the pole face. By measuring the electrical output from load cell the applied force can be estimated [5]. But in this arrangement the load cell will become a part of the electrical assembly. In this paper the load cell is used to establish the relationship between the torque applied on the mounting bolt and the force appearing on the pole face of the thyristor as shown in Fig. 3.

If $N$ number of bolts are used for mounting the thyristor and if the centre of thyristor pole faces coincide with the geometric mean of the bolt arrangement, then the force appearing on the thyristor pole face is given by,

$$F_{Thy} = NF_{bolt}$$  \hspace{1cm} (1)

where, $F_{bolt}$ is the tensile force appearing in one of the bolt while tightening with a torque of $T_{bolt}$. 

Literatures [6]–[8] reported that during tightening roughly 90% of input energy is lost in overcoming the mating friction under the head, nut and mating threads and only remaining 10% of input energy is converted into tensile force in the bolt. To take care this loss in energy a term called Nut factor ($K$) is introduced in the relation between the applied torque and the tensile force created in the bolt and is given by [8],

$$T_{bolt} = KdF_{bolt}$$ \hspace{1cm} (2)

where $d$ is the nominal diameter of the bolt.

Using (2) in (1) the relation between the applied torque on the bolt and mounting force on thyristor pole face is given by,

$$T_{bolt} = \frac{Kd}{N} F_{Thy}$$ \hspace{1cm} (3)

A variety of factors which influences the friction between the thread of bolt and nut influences the value of Nut factor ($K$). Some of the factors influencing are [8],

1) Shape of the threads
2) Friction of the nut against the surface it rotates
3) Type of material and plating used in bolt and nut
4) Presence and type of washers used
5) Type of lubricant used

<table>
<thead>
<tr>
<th>Bolt Condition</th>
<th>$K$ factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-plated, black finish (dry)</td>
<td>0.20 – 0.30</td>
</tr>
<tr>
<td>Zinc-plated</td>
<td>0.17 – 0.22</td>
</tr>
<tr>
<td>Lubricated</td>
<td>0.12 – 0.16</td>
</tr>
<tr>
<td>Cadmium-plated</td>
<td>0.11 – 0.15</td>
</tr>
</tbody>
</table>

**TABLE I.** $K$ factor for various bolt nut conditions

Fig. 3. Various force and torque appearing on the mounting clamp measured using a load cell.
Considering the above factors, values of $K$ for stainless steel material at different conditions are given in Table I [6] where variation of $K$ at each condition is between 15% to 20%. From thyristor datasheets it can be observed that the maximum allowable variation in mounting force is $\pm 10\%$ [9] while some manufacturer allow upto $\pm 20\%$ [16]. When accuracy of torque wrench is considered along with variation in $K$, the set value of mounting force can be outside the datasheet specified limit. This error can be minimized if $K$ is estimated and validated with the fabricated mounting clamps, bolt and nut instead of choosing a typical $K$ from a list such as Table I. Experimental evaluation of $K$ becomes inevitable if the bolt and nut are made of different materials like insulating plastics and composites.

IV. MOUNTING CLAMP FOR PRESS PACK PACKAGE

A. Component for uniform force distribution

It is important that $F_{bol}$ appearing in the individual bolt during tightening of its nut must be transformed as a homogeneous compressive force on the pole face of the thyristor. This is achieved in two steps. In the first step $F_{bol}$ is transformed into a single point compressive force, $F_{Thy}$, and in the second step $F_{Thy}$ is uniformly distributed over the pole face.

a) Single point force: Keeping the pole face in contact with the mounting plate at a single point $F_{bol}$ appearing in all the bolts can be transformed to $F_{Thy}$. Single point contact can be achieved by using a conical cup arrangement between pole face and mounting plate as shown in Fig. 4(a). Ideally this single point should coincide with the centre of the pole face. From the study conducted by thyristor manufacturers [20] the maximum deviation allowable for the position of $F_{Thy}$ can be within $2\text{mm}$ from the centre of the pole face. Hence the pointed tip of the conical cup can be made flat keeping the maximum radius of the flat portion within $2\text{mm}$. The radius of the flat surface appearing on the other side of the conical cup will be equal to the radius of the thyristor pole face.

b) Uniform distribution of $F_{Thy}$. Since $F_{Thy}$ is applied at a single point on the conical cup, the flat surface on the other side of the cone will always see a uniformly distributed force as shown in Fig. 4(a). If $\theta$ is the angle between $F_{Thy}$ and the slanted surface of the cone and $F_s$ is the force acting along the slanted surface of the cone, then various force appearing in the cone are given by,

$$F_s = \frac{F_{Thy}}{\cos(\theta/2)}$$  \hspace{1cm} (4)

$$F_h = F_{Thy} \tan(\theta/2)$$  \hspace{1cm} (5)

$$F_v = F_{Thy}$$  \hspace{1cm} (6)

From (4) and (5) as $\theta$ increases both $F_s$ and $F_h$ increases. If these forces are large then it may leads to deformation to the material. If $\theta$ is very small then the height of the cone will be large and handling such a structure will be difficult. An appropriate value for $\theta$ can be fixed by choosing $F_h$ equal to $F_v$. Substituting, (6) into (5) gives $\theta$ equal to $90^\circ$. For a $90^\circ$ cone its height should be equal to half of its base diameter which is same as the diameter of pole face of the thyristor.

Since height of the $90^\circ$ cone is decided by the pole face diameter, for larger cone height it is split into two (a) upper cone and (b) lower cone as shown in Fig. 4(b). The upper cone is loosely mated with the mounting plate to allow the remaining parts within the thyristor stack to adapt the inherently present non-parallelisms in the heatsink and thyristor surfaces [20].

B. Selection of bolt-nut combination

The manufacturers of bolt and nut will provide the recommended clamp force, $F_c$, for each bolt [6]. If the bolt is made of insulators like Glass epoxy G-10/FR4 or Vetresit® [11] then we need to compute $F_c$ for the selected bolt. Tensile area in $\text{mm}^2$ for a given bolt can be computed approximately as [12],

$$A_t = K_1[d - (K_2 \times p)]^2$$  \hspace{1cm} (7)

where, $d$ is the nominal diameter of bolt in $\text{mm}$ and $p$ is the thread pitch in $\text{mm}$. For a standard bolt [12] the value of $K_1$ and $K_2$ are 0.7854 and 0.9382 respectively.

Clamp force will be approximately $65\%$ of the maximum allowable tensile force, $F_t$, of the bolt [13]. By multiplying the tensile strength, $R_m$ in $\text{N/mm}^2$, specified in the material datasheet with $A_t$ of the bolt gives its $F_t$. Therefore, using (7) clamp force of the bolt is given by,

$$F_c = K_3[d - (K_2 \times p)]^2 R_m$$  \hspace{1cm} (8)

where, $K_3 = 0.65 K_1$.

Shear strength of the nut and bolt material determines the strength of the thread when male threads pulls the female threads or vice versa. Since shear force depends on the cross-sectional area taking part in shearing, by increasing the length of engagement between bolt and nut, shear cross-sectional area can be increased adequately and shearing can be avoided [8].

In long thyristor stack with more than 2 thyristors and their heat sinks, it may be difficult to obtain good mechanical stability with mounting clamp having 2 bolts. In such case it is recommended to use mechanical clamp having atleast 4 bolts. In high voltage applications, these bolts can be made of insulating materials, like Vetresit® , Glass epoxy G-10/FR4. This makes the stack compact compared to stack with metallic bolt since metallic bolt requires more air creepage distance.
and its maximum deflection, \( \omega \) supported rectangular plate is given by, using Navier Method [14], the maximum deflection for a material is assumed to be linear, homogeneous and isotropic. Supported plate is considered in this analysis and the plate shown in Fig. 5(b). To find the worst case deflection, simply sides and applying a force \( F \) deflected. This is equivalent to simply supported plate at two edges, \( F_{Thy} \) then each bolt will experience a tensile force of \( F_{Thy}/4 \). Various forces acting on the mounting plate with \( 90^\circ \) cone and its maximum deflection, \( \omega_{max} \), is shown in Fig. 5(a). The dotted line passing through the centre of the mounting plate represents the line joining the corners of the plate when it is not deflected. This is equivalent to simply supported plate at two sides and applying a force \( F_{Thy} \) at the centre of the plate, as shown in Fig. 5(b). To find the worst case deflection, simply supported plate is considered in this analysis and the plate material is assumed to be linear, homogeneous and isotropic. Using Navier Method [14], the maximum deflection for a concentrated load \( F_{Thy} \) applied at the centre of a simply supported rectangular plate is given by,

\[
\omega_{max} = \alpha \frac{F_{Thy}a^2}{D} \tag{9}
\]

where, \( \alpha \) is a numerical factor, \( a \) is the width of the mounting plate and \( D \) is flexural rigidity of the plate given by,

\[
D = \frac{E t^3}{12 (1 - \nu^2)} \tag{10}
\]

where, \( E \) and \( \nu \) are the Young’s modulus and Poisson’s ratio of the material and \( t \) is the thickness of mounting plate. The numerical factor \( \alpha \) is given by,

\[
\alpha = \frac{1}{2\pi^2} \sum_{m=1}^{\infty} \frac{1}{m^2} \left( \tanh \frac{m\pi b}{2a} - \frac{m\pi b/(2a)}{\cosh^2 \frac{m\pi a}{2a}} \right) \tag{11}
\]

From (11), \( \alpha \) is a function of \( b/a \) and its value is computed for various values of \( b/a \) in [14]. For \( b/a \) equal to 1, value of \( \alpha \) is 0.0116. Hence, the thickness of the mounting plate, \( t \), is chosen for minimum deflection to the mounting plate, computed by (9), due to tensile force in the bolt. The width, \( a \), and length, \( b \), of the mounting plate \( (b \geq a) \) is decided by the clearance required between thyristor and the bolt.

V. Fabrication of Mounting Clamp
The dc voltage rating of crowbar is \( 10kV \) and is realized with 6 thyristors (5STP03X6500 from ABB) connected in series [16]. The pole face diameter of the chosen thyristor is \( 34mm \). The minimum, typical and maximum values of mounting force is \( 8kN \), \( 10kN \) and \( 12kN \) respectively. To improve the electrical conductivity all the metallic parts are fabricated with copper of 99.86% purity. The surface electrical conductivity is improved by surface coating the fabricated copper parts with silver. Since silver tarnishes over time nickel coating is applied over the silver coating.

A. 90° Conical Cup
Since pole face diameter is \( 34mm \) the height of \( 90^\circ \) cone is chosen as \( 18mm \) (rounded the required \( 17mm \) to the next even number). The diameter of one of the flat face of cone is kept to \( 4mm \) where as the diameter of second flat face is same as that of pole face of \( 34mm \). Cone height is measured between the upper flat and lower flat region of the cone. For better adaptation of non-parallelism exists in heatsink and thyristor surface, the cone is split into two portion.

a) Upper cone: Shown in Fig. 6(a) with a height of \( 6mm \), \( 1/3^{rd} \) of the total height of cone. The diameter of the surface mating with mounting plate and the surface mating with lower cone is \( 4mm \) and \( 18mm \) respectively. Using a pin, shown in Fig. 6(a), upper cone is located with the mounting plate.

b) Lower cone: Shown in Fig. 6(a) with a height of \( 12mm \). Its upper face diameter equal to \( 18mm \) and the lower face mating with thyristor pole face have diameter equal to \( 34mm \). Lower cone is mated with the upper cone as well as thyristor using a locator pin.

B. Mounting Bar
The width, \( a \), and length, \( b \), of the mounting plate shown in Fig. 6(b) is chosen to be the same and equal to \( 110mm \) to meet the required clearance from the thyristor. The thickness, \( t \), of the mounting bar is chosen as \( 10mm \). The maximum mounting force, \( F_{Thy} \), of the selected thyristor is \( 12kN \). For the copper material \( E \) and \( \nu \) is chosen as \( 200GPa \) and 0.35 respectively. Using (10) flexural rigidity of the mounting plate is given by \( 11.396 \times 10^3 \text{ Nm} \). Since \( b/a \) is equal to 1, \( \alpha \) is given by 0.0116. Using (9) maximum deflection in the mounting plate is \( 0.1478 \text{ mm} \). Comparing \( \omega_{max} \) with \( a \) or \( b \) of the mounting plate shows that it is approximately 0.14%, which is an acceptable design.

C. Selection of Nut and Bolt
To make the crowbar compact by reducing the creepage distance, the bolt and nut are made of insulating materials. Materials used for the fabrication of bolt and nut are Vetreisit312®
and Vetresit300® respectively, shown in Fig. 7. From the data provided by the manufacturer the tensile strength, $R_m$, of the bolt along machine direction and cross direction are 350 N/mm$^2$ and 100 N/mm$^2$ respectively. $R_m$ for nut in machine and cross direction are same and equal to 220 N/mm$^2$. For the chosen bolt $d$ and $p$ are 10 mm and 1.5 mm respectively. From (8) maximum allowable $F_c$ is 3.769 kN. By considering a safety factor of 80% the maximum allowable tensile force in the bolt ($F_{bolt,max}$) equal to,

$$F_{bolt,max} = 0.8 \times F_c = 3.015 \text{ kN}$$ \hspace{1cm} (12)

Considering the maximum mounting force of thyristor, 12 kN, and four bolt mounting arrangement, each bolt will experience $F_{bolt}$ of 3 kN, which is below the computed $F_{bolt,max}$. Here the shear area between the bolt and nut are improved by choosing the length of the nut equal to two times its diameter.

VI. EXPERIMENTAL EVALUATION

A. Estimation of Nut factor ($K$)

Load cell [5] of 2000 lbf with accuracy of 1% is used to estimate $K$. In the experimental setup shown in Fig. 7, thyristor is replaced with load cell and four numbers of M10 bolt with $d$ of 10 mm made of Vetresit312® are used. The experiment is repeated eight times with a pre-settable torque wrench set to 4.5 Nm and the output voltage from load cell for each iteration is recorded given in Table II. The force acting on the load cell is computed from its output voltage, considering $4V$ equal to 8896 V (2000 lbf). The computed force and the estimated $K$ using (3) for each iteration is given in Table II. The minimum and maximum value of $K$ from Table II are 0.3699 and 0.4110 respectively. By averaging eight values of $K$ given in Table II, the average value of $K$ is given by 0.3875. In a four bolt mounting clamp with $d$ of 10 mm and $K$ of 0.3875, a mounting force of 10 kN can be achieved with 9.68 Nm torque per bolt.

B. Evaluation of uniform force distribution

Uniform force distribution can be confirmed with the help of pressure measuring film from Fujifilm [21]. When pressure is applied on the film a red patches appears. The density of the red colour depends on the amount of pressure applied.

The area where larger pressure is applied will become more denser in red colour and the area where red colour is lighter the amount of pressure applied is low. Suitable film should be selected based on the nominal pressure applied on the film. For a clamp force is 10 kN and pole piece diameter is 34 mm, the pressure applied is 11 N/mm$^2$. For this pressure Low Pressure film (LW) is chosen for the validation of uniform pressure distribution. The experimental setup is same as shown in Fig. 7 except load cell is replaced with pressure measuring film cut to the desired dimension. A torque of 9.68 Nm is applied with torque wrench to the four bolt-nut arrangements. Conical cup used in the experiment are fabricated using Lathe machine as well as Computer Numerical Control (CNC) machine. Fig. 8(a)
and Fig. 8(b) shows the photograph of red patches appeared on the film when conical cup is fabricated with lathe machine and CNC machine respectively. In Fig. 8(a) the pressure is applied only at the centre portion of the thyristor where as in Fig. 8(b) the pressure is uniformly distributed. This also shows the importance of surface flatness and roughness required for uniform pressure distribution. During fabrication of conical cup the surface flatness and roughness are specified as $10\,\mu m$. The complete assembly of thyristor stack and the crowbar is shown in Fig. 9. Voltage, $V_{\text{crowbar}}$ (2kV/div.) and current, $I_{\text{crowbar}}$ (200A/div.) waveform during triggering of crowbar.

VII. Conclusion

Thyristors are to be mounted properly to meet the specifications mentioned in the datasheet. Improper mounting result into higher electrical and thermal resistances and adversely affect its surge current carrying capability. In a crowbar where it operate at high $di/dt$ and surge current rating proper mounting becomes essential and it becomes critical when thyristors are series connected. The paper discusses the mechanical design method for the fabrication of mounting clamps for press pack package thyristor. The paper also detailed the method to establish the torque-force relationship especially needed when the bolt is fabricated with non-metallic material. A detailed procedure for the evaluation of mounting clamps is explained in the paper and established the importance of surface flatness for uniform force distribution. Based on the formulated design method a compact mounting clamp is designed and fabricated for $10kV$, $1kA$ crowbar. Electrical performance of crowbar is tested and it meets the system requirements.

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