Protecting the power transmission grid

Mitigating the threat of high-powered ballistic attacks on power transformers

ABSTRACT

Power transformers are vital pieces of equipment in the power grid. However, the measures taken to safeguard these critical transmission nodes from high-powered ballistics are often insufficient. This article presents the threat that ballistics attacks pose to transformers and the consequences such attacks may have on the broader power grid. The physical protection measures available to transmission system operators are then discussed, including a tank-mounted transformer protection system.

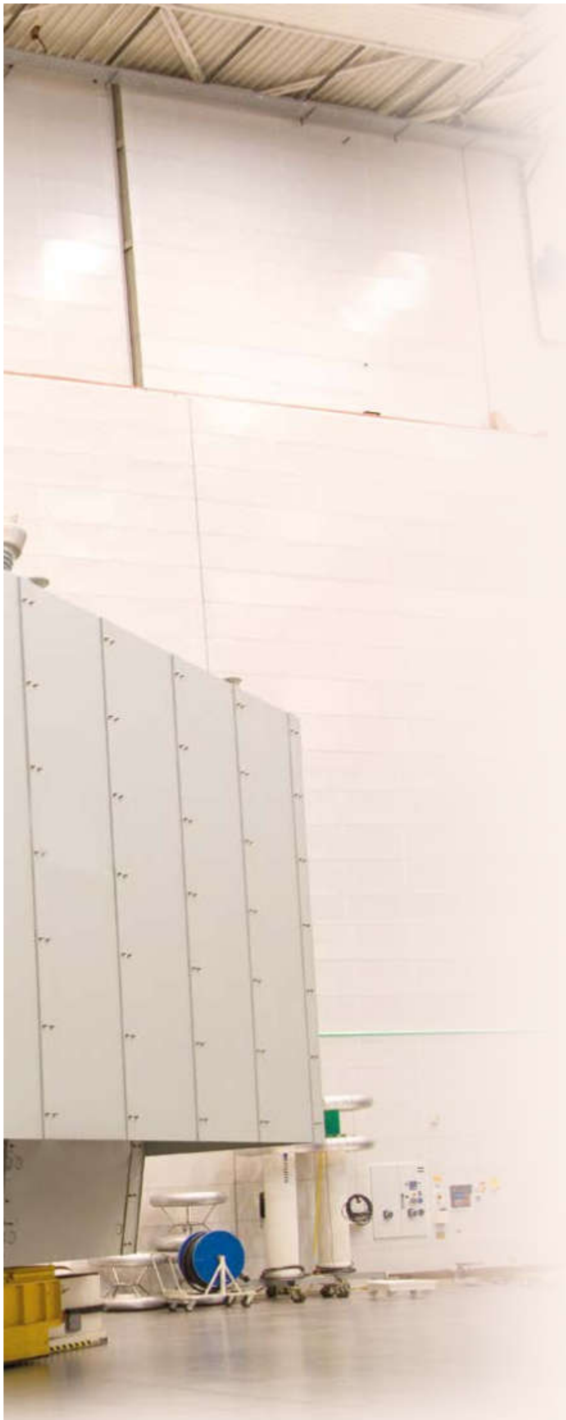
KEYWORDS

bullet resistance, power transformers, grid resilience, high-powered ballistics

1. Introduction

Serving as critical nodes in the power grid, transformers have been engineered over the past decades to withstand operational risks, such as lightning strikes, severe weather events and network power fluctuations. However, often housed in substations protected by a simple chain-link fence, transformers present an easier target for malicious attacks than other key network components. Furthermore, to mitigate the threat of an attack on a transformer, current standards and guidelines generally focus on assessing, preventing, detecting and responding to unauthorised access to substations. These measures therefore do little to safeguard transformers from threats that originate outside a substation's perimeter.

There is consensus among utility operators, governments and manufacturers that transformers are highly vulnerable to ballistics attacks. With a clear line of sight, attackers may employ high-powered rifles to disable these critical pieces of equipment from a significant distance. Such rifles are easily capable of penetrating the standard 8 mm to 10 mm thick transformer tanks, causing the loss of insulating and cooling oil (which is critical for the operation of the transformer) or potentially short-circuiting the windings and destroying the



The threat of high-powered ballistics to transformers must be mitigated in order to safeguard national power grids from the risk of widespread and extended blackouts

unit. Other components of the transformer, such as the bushings and cooling systems, may also be targeted.

The vulnerability of transformers has been demonstrated by several successful attacks in recent years. The most highly publicised of these assaults occurred in 2013 at a major U.S. substation in San Jose, California. Carried out with a high-powered rifle, the attack was able to knock out 17 large power transformers in approximately 19 minutes, resulting in USD 15.4 million in damages. It took utility workers 27 days to make repairs before reopening the substation.

The San Jose and other attacks have highlighted the possibility that, if carried out simultaneously on several substations, assaults with high-powered ballistics could have severe implications for reliable service over large geographic areas. The U.S. Federal Energy Regulatory Commission has noted that such an attack could cripple the U.S. electricity network and cause widespread, extended blackouts. This would have serious economic and social consequences, thereby making a coordinated attack on several substations a potential target for terrorists. Best practice to ensure the reliable operation of power transmission networks is therefore to safeguard transformers from intentional damage.

2. Available protection measures

To protect transformers from high-powered ballistics it is necessary to place a bullet resistant structure in the line of sight between the assailant and the unit. Several such measures are available to transmission system operators and asset owners, including:

- masonry walls
- ballistic barriers
- direct hardening of the transformer tank
- tank-mounted armour panels

Each of the abovementioned measures has advantages and disadvantages that must be considered when deciding on the optimal solution to protect critical pieces of transmission equipment.

2.1 Masonry walls and ballistic barriers

A protection measure readily available to utility operators is the construction of masonry or ballistic walls around either an entire substation or a critical unit. The practicality of these solutions however is heavily dependent on the geography, topology and layout of a specific substation. In particular, the most vulnerable substations are those exposed to an open hillside or elevated area, which allow for a direct line of sight to key infrastructure. In such cases the placement of bullet resistant barriers must be meticulously planned to obstruct the line of sight, otherwise the protection measures are obsolete, as illustrated in Figure 1.

As shown in Figure 1, both masonry walls and ballistic barriers limit the visibility of the assets and may provide varying degrees of bullet resistance. However, these measures can also limit the ability of security personnel to identify saboteurs once inside the premises. Furthermore, masonry and ballistic walls require foundations, which may result in a timely and costly bullet resistant solution. It is also of note that concrete barriers do not provide a viable option for the high level protection of transformers as they are not able to withstand several ballistic impacts, as required by ballistics standard UL 752 [1].

2.2 Direct hardening of the transformer tank

An alternative bullet resistant approach to fixed, external masonry or ballistic walls is to directly harden the transformer tank; i.e. manufacturing the transformer tank from a bullet resistant material allows for protection of the unit's core and windings, being the most critical components. Furthermore, standard bushings may be replaced with polymer or composite resin-impregnated paper (RIP) oil-less type bushings to ensure that even

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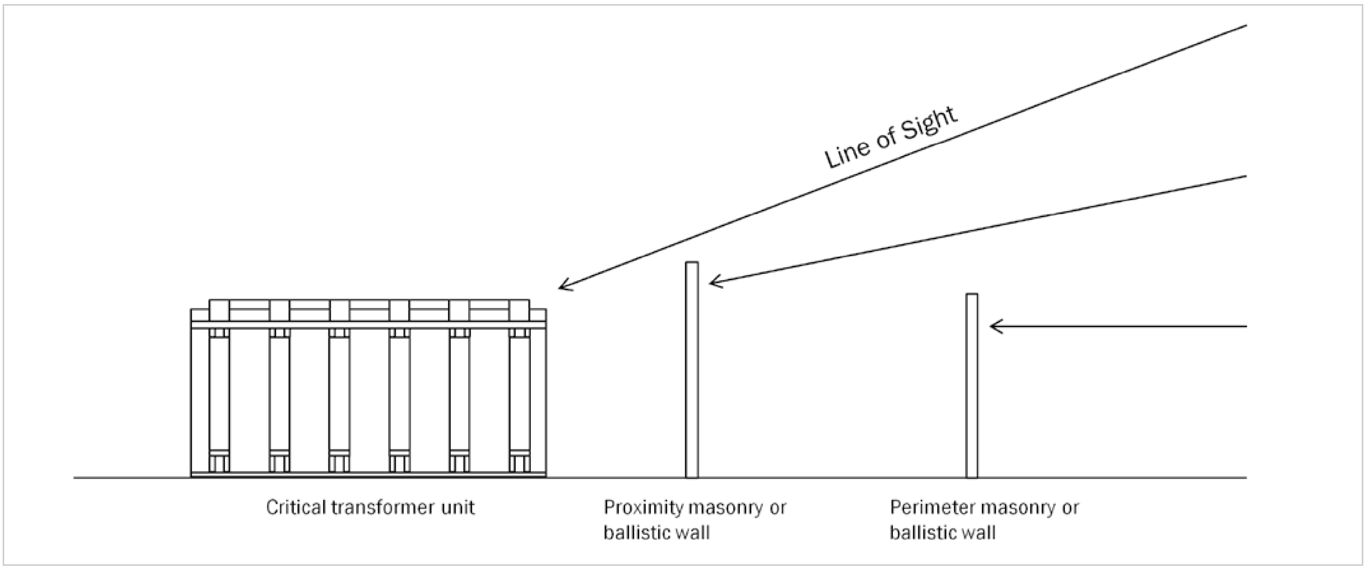

Figure 1. Influence of masonry and ballistic wall position on obstructing the line of sight

The practicality of ballistic protective solutions is heavily dependent on the geography, topology and layout of a specific substation

if the polymer insulator is penetrated, catastrophic failure will not result in ignition of the oil.

A secondary advantage of the hardened tank concept is that, as opposed to external protection measures, a transformer with a hardened tank may show no visual difference to a standard unit. An assailant is therefore unable to determine the significance of a unit from its appearance. Additionally, with the tank performing the function of the bullet resistant structure, no line of sight between an assailant and the transformer's active part is left unprotected.

Despite the significant advantages of hardening the transformer tank, there are also several drawbacks. The primary disadvantage of tank hardening is that the cooling equipment, such as radiators and fans, remain exposed to ballistic attack. This is a critical issue as highlighted by the 2013 attack on the San Jose substation. During this assault the assailants targeted the radiators, causing a loss of insulation oil and rendering the transformers inoperable. To overcome the exposure of the cooling equipment, transformers with hardened tanks must be fitted with impact sensors and automated cooling valves. Such devices allow for a ballistic attack to be detected and for appropriate actions to be taken.

With regard to the hardened tank concept, it is only feasible that new units are equipped with such a protection measure. This is due to the tank forming an integral part of the transformer. Therefore, units already in operation, although they may be of critical importance to the transmission network, remain exposed to attacks with high-powered ballistics. It is also of note that particular attention must be given to the welding seams and/or other jointed areas when employing a bullet resistant tank, as such areas may exhibit lower bullet resistant characteristics.

2.3. Tank-mounted bullet resistant panels

The final bullet resistant solution discussed in this article is that of tank-mounted bullet resistant panels. This protection measure is characterised by bullet resistant panels supported on brackets that attach directly to the stiffening ribs on the transformer tank. The system may therefore easily be installed onto new units and permits the design to be retrofitted onto critical transformers currently in operation. Furthermore, overlapping panels or an addition strip of material may be employed to offset lower bullet resistant properties at jointed areas. An illustration of a transformer protected with tank-mounted bullet resistant panels is presented in Figure 2.

As shown in Figure 2, tank-mounted bullet resistant panels negate the need for foundations while protecting the tank, cooling equipment, conservator, turrets and the bottom of the bushings. As with the tank hardening concept, standard porcelain bushings may also be replaced with polymer or composite RIP oil-less type bushings to eliminate the risk of fire. However, in contrast to direct hardening of the tank, the bullet resistant panels are able to protect external equipment, including fans and radiators. This nullifies the need for the transformer to be fitted with components such as impact sensors and automated cooling valves.

Mounting the bullet resistant panels directly onto the transformer tank ensures that, unless the topology is highly unfavourable, a direct line of sight to the transformer is not possible. Furthermore, the concept is significantly more space efficient than a fixed external masonry wall or ballistic barrier. This is because major maintenance works require only a minimal number of panels to be removed while sliding doors in front of the control cabinets and pumps allow for ease of access during operation, as shown in Figure 3. In contrast, fixed external masonry walls or ballistic barriers must have a sufficient offset from the transformer to allow for all maintenance activities to be conducted.

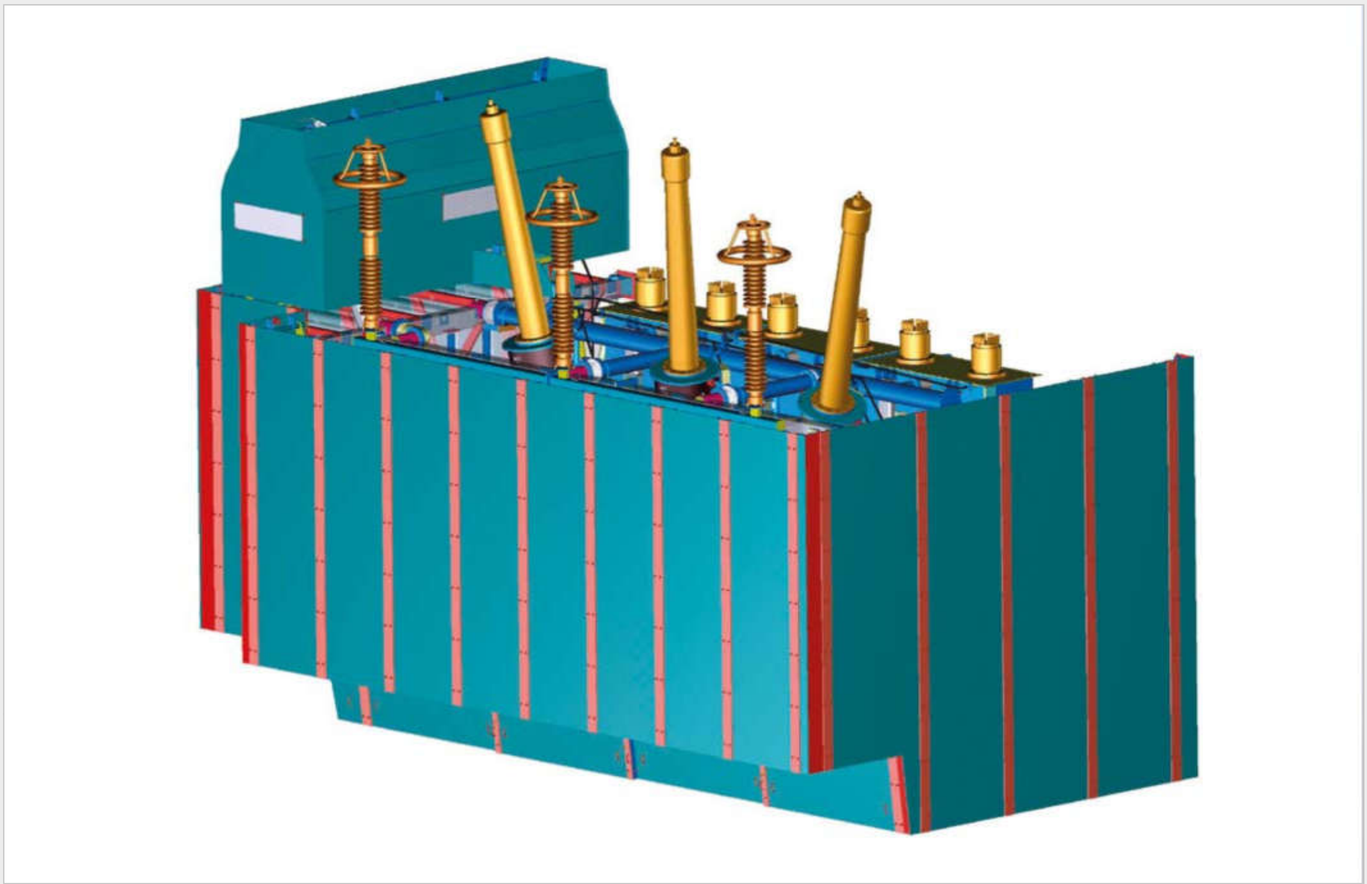

Figure 2. Transformer with tank-mounted bullet resistant panels

The advantage resulting from the space efficiency of the tank-mounted panels is that the system may be used to safeguard equipment in confined areas. This characteristic is becoming increasingly important with the trend of locating critical electrical infrastructure in urbanised environments. The only design parameter that must be carefully considered when employing the system in confined spaces is the efficiency of the cooling system. This is especially true when retrofitting the solution onto units that feature fans mounted on the side of the radiators for horizontal forced air flow.

Several options are available to protect critical units, including ballistic walls, direct hardening of the transformer tank and tank-mounted bullet resistant panels

3. Bullet resistant materials

Based on security specifications and functionality requirements, several materials have been engineered to provide bullet resistance characteristics. The majority of commonly employed bullet resistant materials can be categorised as follows:

- glass and glazed plastics
- fibreglass composites
- steels

In addition to application and ballistic performance, the economic costs of the various measures available must also be taken into account when protecting critical assets. As previously discussed in this article, concrete barriers do not provide a viable option for the high level protection of transformers and are therefore not considered in the above list as a bullet resistant material.

With regard to bullet resistance, glazed and glass materials generally only protect against small-arms fire and are used when visual contact is needed with the protected area. The characteristics of such materials are therefore not required or suitable for protecting critical transmission equipment, which are vulnerable to high-powered ballistics attacks. As opposed to glazed and glass materials, fibreglass composites are able to provide a higher degree of bullet resistance. These materials are usually incorporated into structural designs and may therefore be integrated into ballistic walls. However, it is not feasible to construct hardened transformer tanks or tank-mounted bullet resistant panels from fibreglass composites.

Although more advanced materials are available, steel is still dominant in the design of protective structures and is the preferred material for safeguarding critical transmission equipment. This is due to the high absolute strength and hardness of the material, combined with high ductility, formability, and durability [2]. These characteristics allow steel to be used in the construction of hardened transformer tanks or external protection measures, such as ballistic walls or tank-mounted panels. Furthermore, steel often provides a more cost effective bullet resistant solution than other materials [3].

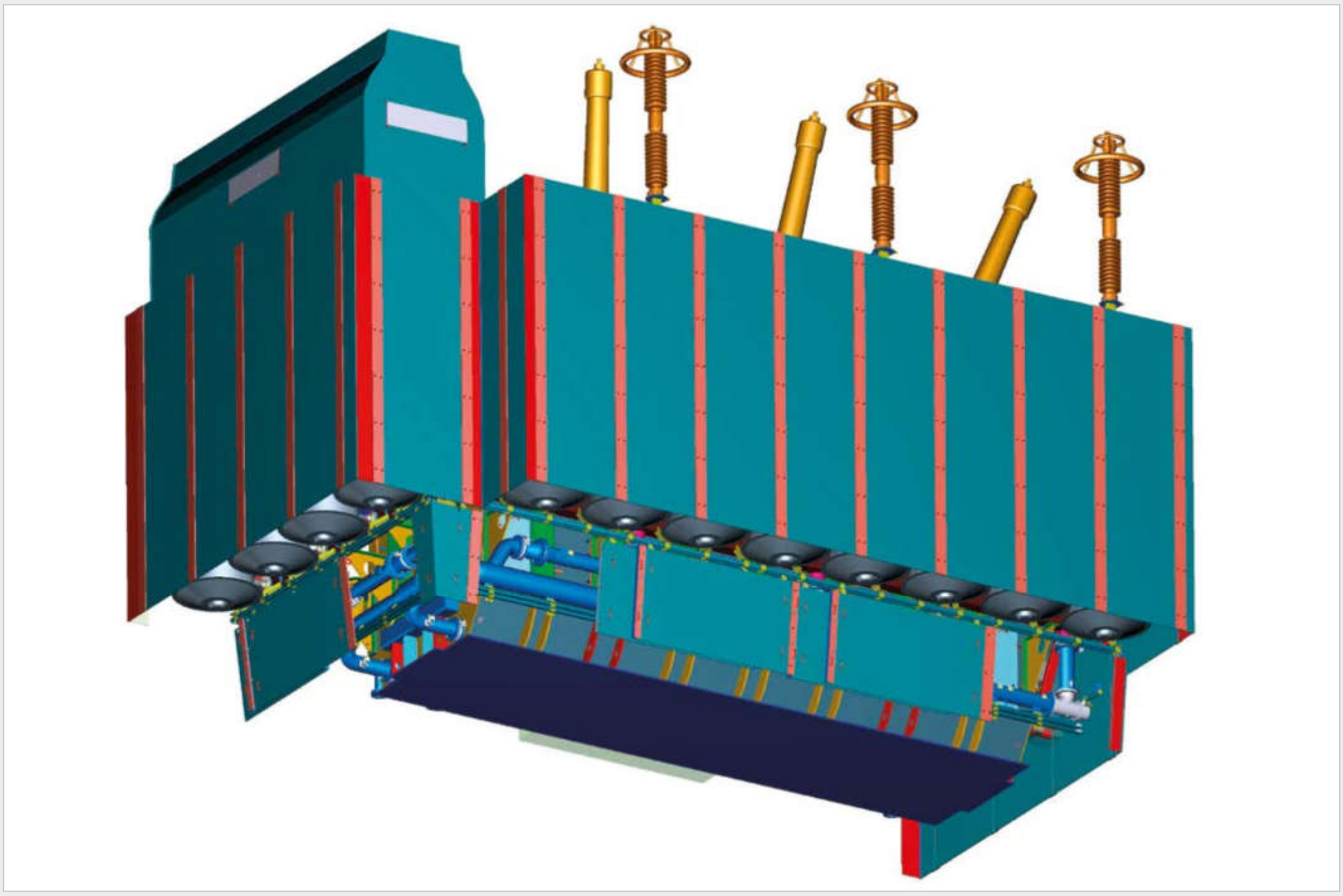

Figure 3. Sliding panels in front of control cabinets and pumps for ease of access

Glazed and glass materials only protect against small-arms fire; fibreglass composites provide a higher degree of bullet resistance, but steel is still the preferred material for protecting transmission equipment

As with the other categories of bullet resistant materials, not all steels exhibit the same bullet resistant characteristics. Steel alloys that exhibit higher hardness, impact strength and tensile strength – generally providing increased bullet resistance – are also characterised by decreased ductility, toughness and weldability [2]. Further reading on the properties of armour steel over a range of steel hardness values may be found in specifications including Australian DEF(AUST) 8030 [4] and UK DEF STAN 95-24 [5].

From the factors considered, it can be seen that the choice of bullet resistant steel alloy used in protecting transmission equipment is a function of application, ballistic performance, weight and price. Due to the lack of predictive methods, it is also important to thoroughly test materials (including welding seams and other joints) to assess the required ballistic withstand properties. These tests are generally conducted in accordance with predefined standards.

4. Physical safety standards

The purpose of standards is to serve as a mutually agreed upon methodology or set of parameters to define an industry's best practice. With regard to critical transmission equipment, standards that describe the testing of bullet resistant materials allow for utility operators and federal agencies to specify threat levels which are to be mitigated. Two prominent bullet resistant material testing standards are UL 752 [1] and VPAM APR 2006 [6], used principally in the U.S. and Europe, respectively. In many aspects these standards are comparable, as shown in Table 1.

The materials employed in protecting transformers from high-powered ballistic attacks may be specified in accordance with both VPAM APR 2006 and UL 752. Through extensive testing and development programs bullet resistant barriers, hardened tanks and tank-mounted panels may all be produced to withstand the highest class of rifle projectile specified in the aforementioned standards, being a .50 calibre round. The .50 calibre round represents the most powerful commonly available cartridge that is not considered a destructive device under the National Firearms Act enforced by the U.S. Department of Justice.

With regard to establishing the bullet resistance specifications for an individual transformer, transmission system operators should consider the maximum likely ballistic threat posed to a unit. In the U.S. this maximum likely threat may be represented as a .50 calibre round, being the most powerful commonly available

Table 1. Comparison of projectiles specified in UL 752 and VPAM APR 2006

	Standard	Rating	Ammunition		Bullet velocity
			Type	Mass	
.308 calibre rifle bullet	UL 752	Level 8	Full metal copper jacket, military ball, lead core	9.7 g	838 m/s
	VPAM APR 2006	Class 7	Full metal jacket, pointed bullet, soft core	9.55 g	830 m/s
.50 rifle calibre rifle bullet	UL 752	Level 10	Full metal copper jacket, military ball, lead core	45.9 g	856 m/s
	VPAM APR 2006	Class 13	Full metal jacket, pointed bullet, hard core	43.0 g	920 m/s

cartridge. However, other geographic regions may face differing threat levels. It is also of interest to note that the attack on the U.S. substation in San Jose, California was conducted with a standard .30 calibre rifle, which is widely available and commonly used as a hunting rifle.

Conclusion

The threat of high-powered ballistics to transformers must be mitigated in order to safeguard national power grids from the risk of widespread and extended blackouts. Several options are available to transmission system operators and asset owners in order to protect critical units, including ballistic walls, direct hardening of the transformer tank and tank-mounted bullet resistant panels. Each of these aforementioned measures is able to withstand the maximum likely threat posed by a ballistics attack. Therefore, utility operators and owners must consider the feasibility of each solution with respect to the topology of an individual substation, the ability to retrofit the solution to critical units already in operation, and the time scales and costs involved with protecting critical pieces of infrastructure.

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