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The Economics of Swarm Defence: Integrating High-Power Microwave Weapons into India's Multi-Layered Defence Grid

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Abstract

Op Sindoor highlighted the growing threat posed by low-cost swarm drones and the economic inefficiency of relying solely on expensive kinetic interceptors for air defence. This issue brief argues that High-Power Microwave (HPM) systems offer a cost-effective, non-kinetic solution for India to counter future drone swarms and strengthen its self-reliant air defence capabilities.

Keywords: High-Power Microwave (HPM), Swarm Drones, Air Defence, Operation Sindoor, Aatmanirbhar Bharat

Introduction

Operation Sindoor marked a historic moment for India's Air Defence System. Over a four-day period, Pakistan launched an estimated 300 to 400 drone attacks across 36 locations in order to overwhelm Indian air defences (Zee Business, 2025). India's Integrated Air Command and Control System (IACCS), along with Counter Unmanned Aerial Systems, shoulder-fired weapons, legacy air defence weapons and modern air defence systems successfully countered these attacks (Operation SINDOOR, 2025).

Yet, the operation highlights a growing concern. The proliferation of low-cost unmanned aerial systems and cheap FPV swarm drones has fundamentally changed the economics of aerial warfare. An unavoidable challenge emerges multi-million-dollar traditional kinetic interceptors to engage with **cheap expendable swarm drones** (Kanu et al., 2024; Prabhune & Jaiswal, 2024). Such economic asymmetry poses a concern for India to counter prolonged swarm attacks without compromising the security of its air littoral. Here, the High-Power Microwave (HPM) system offers a non-kinetic, near-zero operational-cost solution, making it suited to counter swarms. India's "Aatmanirbhar Bharat" (self-reliant India) vision demands developing and acquiring such a critical system to create a safer airspace against its adversaries.

This issue brief examines the HPM system's operational mechanism, limitations due to atmospheric conditions, thermal and terrain effects concerning India's geography, and its current global possession. It then analyses why swarm drones remain vulnerable to HPM, revisits Operation Sindoor's operational realities, and presents an economic breakdown demonstrating that HPM acquisition is not merely advantageous but essential to secure India's national interest in any future drone swarms.

High Power Microwave System

The High-Power Microwave system is a directed-energy weapon (DEW) that is capable of generating and emitting intense pulses of electromagnetic energy that exceed 100 megawatts (MW) of peak power output within the frequency range of 1 GHz to 300 GHz (Schamiloglu, 2004). HPM works by producing microwave emissions through very short pulses, producing high power densities at the target that overwhelm and disable sensitive semiconductor electronics.

The HPM system induces damaging currents and voltages in a target's internal electronics by coupling electromagnetic energy through two distinct pathways, front-door coupling and back-door coupling. Through front-door coupling, energy enters through the target's antennas, sensors and other apertures that are designed to receive electromagnetic signals, while through back-door coupling energy passes through seams, cables and apertures within the target's physical structure. Once they couple inside, the voltage induced causes several disruptions, such as forced processor reboots or communication loss, to thermal burnout of semiconductor junctions, transistors and CMOS circuits, causing permanent damage (Shurenkov & Pershenkov, 2016).

The most recent significant technological transformation in HPM has been its shift from conventional vacuum-tube-based source to solid-state gallium nitride (GaN) semiconductor technology. Early vacuum electronic devices required a high-voltage pulsed power supply and bulky magnetic field systems. Their output power was limited due to pulse shortening. The switch to gallium nitride (GaN) semiconductor technology allowed for 10 times more power-handling capabilities than its predecessor; it is capable of operating at higher voltages around 50-70 V while producing output pulses exceeding 5 watts per millimetre of device periphery (Kneen, 2020; Oncea, 2025). This led to new generation HPM systems that are more compact, reliable and controlled than the early generations.

Solid State HPM systems such as the Eprius Leonidas developed by US company Eprius have GaN solid state architecture-based power amplifiers that provide rapid fire rate that eliminates the need for physical reloading, causing instantaneous effects on targets without getting overheated (Litnarovych, 2025; Oncea, 2025).

How does an HPM hit its target

The HPM system works by emitting a pulse that illuminates a target and generates electromagnetic field-induced currents and a voltage surge on the internal conductors, circuit traces and junctions of the target's internal electronics (Shurenkov & Pershenkov, 2016). The amount of damage the target endures depends on its internal electronics, whether it's bipolar junction transistors, MOSFETs, CMOS integrated circuits or a combination of all three. The severity of the damage ranges from communication loss to thermal runaway-led short circuits depending upon the HPM system's output power density.

A single HPM pulse can affect multiple targets simultaneously within its area coverage, making it the optimal choice for counter-swarm operation, disabling every drone within its beam direction rather than engaging with individual targets like DEW lasers or other conventional kinetic systems.

Limitations and effects in respect to HPM Systems

Atmospheric effect on HPM System

The propagation of shorter-wavelength, high-frequency microwaves through the Earth's lower atmosphere (12 KM altitude) is affected by molecular absorption. Frequencies ranging between 1 and 300 GHz are affected by water vapour lines at 22 to 183 GHz and oxygen lines between 60 GHz and 118 GHz (Janssen, 1993). However, the impact of atmospheric gases is minimal for HPM systems that operate at frequencies lower than 10 GHz. (L band, S band and C Band).

The Swedish Defence Research Agency (FOI) concluded that HPM propagation from source to target during weather conditions such as rain and fog has little effect on microwave pulses that operate on frequencies below 10 GHz (Johansson, 2003). FOI's study also concluded that theoretically an HPM system operating below 10 GHz should have an operational range that stretches tens of kilometres, similar to that of a surface-air-missile.

This shows a comparative advantage of the HPM system over other laser-based directed-energy weapons such as laser systems that remain vulnerable to long-range engagement due to energy degradation caused by aerosols, fog and precipitation.

Effect of temperature on HPM system

The shift of HPM technology from vacuum-tube sources like klystrons and magnetrons to solid-state gallium nitride (GaN) amplifiers introduced thermal vulnerabilities. The output electromagnetic radiation is not affected by the temperature of the surrounding area, but the semiconductor device made with high-electron-mobility transistors (HEMTs) itself is temperature-sensitive. When the system temperature reaches above 250K, the device's electrical performance starts to degrade over longer usage (Shen & Cao, 2024).

In high-temperature environments such as the Thar desert, where the ambient temperature exceeds 45 C (318K), solid-state HPM systems without an active cooling system will have considerable performance disadvantages. On the contrary, in the high-altitude environment such as Ladakh, where the average temperature is 15 to 17 C and can fall below -30 C, modern HPM systems can achieve peak power performance without the need for cooling elements.

Terrain and Surface Effects on HPM

Terrain and Surface have an additional effect on microwave propagation. Irregular terrain can produce both destructive and constructive interference. An irregular terrain with significant ground bounce can achieve a 2.3dB that is approximately a 70% increase in power density at the target site (Rodenbeck et al., 2022). This implies that, if placed tactically with knowledge of local terrain features, an HPM system can achieve greater effective range.

Key players currently possessing HPM technology.

The global HPM weapons market features systems primarily from the United States, China, and Russia. In contrast to most weapons systems which have both a high purchase price and a high operating or engagement cost, procurement cost of a typical DEW-HPM system e.g, IFPC-HPM (Epirus Leonidas), the cost comes to around \$15-\$25 million per unit while its operating cost per unit shot is just zero point five cents (\$0.05) (*Microwaves vs. Drones*, 2025), while a SM-3 missile will be around \$10-\$12.5 million and a single Arrow-3 interceptor will be \$2-\$4 million (Fetter & Wright, 2025). This **penny-per-kill economics** of HPM provides a viable alternative to deploying against massive cheap swarm drone attacks.

Epirus Leonidas (USA) - It is a solid-state, software-defined HPM system built using gallium nitride (GaN) amplifiers; developed in multiple variant IFPC-HPM (Indirect Fire Protection Capability-High Power Microwave) (*Epirus*, 2025; *Epirus C*, 2025; *Epirus B*, 2025) for the US Army, ExDECS for the Navy/marine corps and the Leonidas-H2O for maritime interdiction. **THOR** (Tactical High-Power Operational Responder) (USA) - Designed for the U.S Air Force to defend against drone swarms. THOR's compact, transportable design. Its capabilities of using bursts of high-power microwaves were demonstrated against a swarm of drones in April 2022 (Maksymov, 2025).

CHAMP (Counter-Electronics High Power Microwave Advanced Missile Project) (USA)- An air-launched HPM system designed and manufactured by Boeing for the U.S Air Force. It is designed to be carried by cruise missiles and aircraft in order to destroy enemy electronics from a short range (*Global Market Monitor*, 2025).

Phaser (USA) - A high-power microwave system developed by Raytheon to be used as part of a counter-UAS (unmanned aircraft system) mission or as an electronic attack asset (*Global Market Monitor*, 2025).

Hurricane-3000 (China) - reportedly generates an 80,000 volt/meter output equivalent to that produced by nuclear electromagnetic pulse (EMP) devices (Baruah, 2025).

RANETS-E (Russia) - High-power pulsed (HPM) air defence weapon system, unveiled by Rosoboronexport in 2001. This weapon is capable of generating a 500-megawatt pulsed HPM having a range of over 20 miles against unprotected targets and 10 miles against protected targets (Delgado, 2018).

HPM effectiveness against swarm drone attack

Commercially available small drones are the protagonists of staging a drone swarm attack. It has challenged the economics of war. Such drones are cheap; they can be produced in thousands, and most importantly, they are disposable. The strategy behind such attacks is to overwhelm the costly air defence system of the enemy. Traditional air defence systems like Stinger missiles, Akash missiles or even DEW laser systems engage kinetically with their targets. In case of a swarm attack, such a system often finds itself being overwhelmed by the sheer number of drones that are trying to pass through the airspace, some often carrying small munitions. In such cases, to counter countries often rely on legacy weapons such as, the Indian army has modified the L-70 Bofors paired with upgraded fire-control radars as part of their Integrated Counter UAS (Unmanned Aerial Systems) Grid to kinetically engage with each drones (*SWARAJYA*, 2025), but they have a core limitation, such systems are one to one systems, that is they have to engage with each drones individually. This makes such a legacy system vulnerable to saturation attacks where the number of drones climbs to thousands. Such large numbers overwhelm the system's capacity, creating gaps in the airspace that can be exploited.

The Russia-Ukraine conflict saw one of the biggest swarm drone operations; both sides used hundreds of cheap drones to carry out attacks on each other. Since then, they have become more and more commonly used in almost every major conflict: the Iran-Israel Conflict, the India-Pakistan conflict. During Operation Sindoor, Pakistan launched over 400 drone attacks in India's western and northern frontier (Peri, 2025). These drones, being cheap, are fundamentally the driving factor behind such attacks, as it creates an economic asymmetry between cheap attacking fpv drones being intercepted by air defence systems that cost millions to operate. Although off-the-shelf equipment that are used to manufacture such drones isn't inherently immune to HPM systems.
Protection against HPM systems requires Electromagnetic pulse/induction (EMP/EMI) hardening measures. There are primarily two ways of EMP hardening: shielding and filtering.

There are several methods of HPM hardening, such as a faraday cage, optical and fibre-optic datalinks, filtering signal lines and plasma shielding. Even with the combined effort of some of the practical measures, it can only increase the threshold against HPM attack; it cannot make a drone invulnerable. An HPM system with software-enabled power adjustment can close the range or exploit the shielding threshold of such drones because such commercial drones simply don't have enough power that can have a higher threshold for HPM output exceeding hundreds of megawatts.

Economic and Physical constraints of HPM Hardening for Drones

In reality, some form of partial HPM hardening is done on only high-value military aircraft like F-22 and F-35 or large ISR UAVs in order to protect against nuclear EMP. Small technical UAS (Group 1/2/3) and MALE drones are not hardened beyond basic EMI filters, but a powerful HPM pulse can disable key internal systems.

For drones commonly used in swarms, the driving factor is it needs to be cheap enough to be acquired in large numbers and attritable, meaning that the whole strategy to overwhelm the air defence system is designed around a high loss rate.

There are two principal problems to making such drones immune to HPM attacks.

1. The economic factor: The cost of getting a drone effective HPM hardening that includes multiple methods such as conductive enclosures (Faraday Cage), filters and fibre optics controls additional thousands of dollars to the basic cost of a small drone. So, if a standard FPV drone costs $400, its hardening process will add $5000 to $10,000 to the unit cost of the drone (DEPARTMENT OF DEFENSE, 2007; Ramsey_Em2ax, 2025). At that price point, even a swarm of 100 drones would cost over $500,000 to $1,00,000, this loses the decisive cost advantage that makes swarms strategically attractive. HPM protection is not economically compatible with mass-produced disposable swarm drones. As a result of which the class of drones that are typically used in swarm attacks, such as the Shahed 136, Lancet, and commercial FPVs, are not HPM-resistant.

2. The weight factor: another criterion that makes a swarm drone a popular choice is the ability to attack adversaries with hundreds of lightweight drones that carry a small payload which is ideally small explosives. According to experts, the added weight of HPM hardening will drastically increase the weight of the drones and reduce their range and payload capacity. This makes widespread swarm attack unfeasible (Burdon & AIR COMMAND AND STAFF COLLEGE, 2017).

Pakistan has inventories of Chinese CH-4 and Wing Loong II MALE drones, and its indigenous Burraq. There is no report of HPM-specific hardening (‘Pakistan’s Vaunted UAV Fleet Falters’, 2025).

Turkey is one of the biggest producers and the second biggest exporter of cheap off-the-shelf drones after Pakistan. Its biggest inventory Bayrakter TB2, runs on commercially available avionics, and these are not HPM-hardened (News18, 2025). Turkey is currently developing a class of jet-powered UCAV called Kızılelma, which reportedly has counter-jamming measures but has no HPM hardening measures.

China has a wide range of indigenous drones, including CH-4, CH-5, Wing Loong series as well as the stealthy WZ-8 and other various swarming munitions, but there has been no open-source evidence on HPM-specific hardening on such weapons. (WIPO, 2023).

Relevance & Implications of Operation Sindoor

After India launched Operation Sindoor early on 7th May 2025, Pakistan retaliated by targeting multiple Indian military and civilian infrastructure across northern and western fronts using drones and missiles. Its army deployed a range of advanced weaponry systems, including PL-15 missiles (Chinese origin), Turkish-origin UAVs (named Yiha/Yeehaw), long-range rockets, quadcopters and commercial drones. All of such targets were neutralised by India's Integrated Counter UAS Grid and indigenous AD (Air Defence) systems like the Pechora, OSA-AK and LLAD guns (Low-level air defence guns), Akash Missiles and electronic warfare networks (Operation SINDOOR, 2025). On 12th May 2025, post Operation Sindoor briefing, Lieutenant General Rajiv Ghai, Director General of Military Operations, highlighted the excellent performance of India's Comprehensive Multi-Layered Air Defence System that helped prevent Pakistan Air Force attacks on Indian airfields and logistic installations. The Integrated Air Command and Control System (IACCS) of the Indian Air Force brought all these elements together, providing the net-centric operational capability vital for modern warfare (Operation SINDOOR, 2025).

India's Comprehensive Multi-Layered Air Defence System

India has a comprehensive and multi-layered air defence shield. This involved the coordinated employment of a wide array of systems, from long- range SAMs to upgraded legacy guns and specialised counter-drone technologies. The Russian-origin long-range Air Defence System **S-400 Triumf** ("Sudarshan Chakra") is the first line of the Indian military's defence perimeter with a range of 400 kilometres (The Times of India, 2025). The Indo-Israeli joint development **MRSAM** (Medium Range Surface-to-Air Missile) is the second line of defence. It has a range of 70 km. India's **Akash surface-to-air missile system,** deployed by the Army and Air Force across the western border and LoC, acts as the third line of defence responsible for shooting down numerous drones and low-flying missiles within its 25 to 40-kilometre engagement zone (The Indian Express, 2025).

The old L-70 Bofors 40mm cannon and ZSU-23-4 Shilka 23mm gun, which were originally Soviet-era weapons but later greatly improved with modern radars, electro-optical sensors, and automatic tracking systems, were used in direct action against low-flying Unmanned Aerial Vehicles (UAV) and drone swarms. DRDO Anti-Drone Systems/Counter-UAS (C-UAS) Grid: In addition to conventional guns and missiles, India army has deployed C-UAS equipment to create an Integrated Counter-UAS Grid. They included sophisticated radar and electro-optical sensors for detecting and tracking drones, as well as non-kinetic means such as jammers (disrupting command and control or navigation signals such as GPS), Man-Portable Counter-Drone Systems (MPCDS) (Operation SINDOOR, 2025).

The need for HPM systems post Op Sindoor

During Operation Sindoor, India's Air Defence System performed with exceptional synergy and stood out as a testament of strength, foiling multiple retaliation attempts by Pakistan. As part of India's offensive Strategy, it deployed loitering munitions such as kamikaze drones, each successfully striking critical enemy targets that included radar and missile systems. The 4-Day Operation highlighted the Indian Armed Forces' superior tactical planning and execution, neutralising threats using both kinetic and non-kinetic tools.

However, the operation relied on a critical strategic vulnerability. The challenge of economic asymmetry of drone swarm attacks. Pakistan retaliated to India's attack with swarming tactics, it launched an estimated 300 to 400 drones across 36 locations in order to overwhelm Indian air defences (Zee Business, 2025). While India did successfully counter these attacks, the underlying math is concerning. The use of sophisticated interceptors and firing multi-million dollar SAMs to kill a $1000-$20,000 drone creates a severe cost-asymmetry dilemma (ÜÇOK, 2026). A larger aggressor with huge industrial capabilities and a massive inventory of disposable drones can exhaust a defender's resources.

For an adversary nation like Pakistan, which is facing severe economic constraints and industrial challenges, a prolonged high-intensity drone war may not be a practical choice. But, unlike Pakistan, China possesses advanced technological infrastructure and immense production capacity to weaponise prolonged drone swarm attacks on a larger scale. Beijing has been actively developing systems like "Atlas" capable of launching 96 from a single mobile platform (Gokce, 2026). China dominates over 80% of global small drone production, giving it a massive advantage in the scale of fpv drone production (News18, 2026). With such might, China can sustain a multi-phase swarm attack that is designed to repeatedly saturate its adversary's air defence system.

In case of a high-level conflict between India and China, India's current cost asymmetry would shift drastically against it. Even if an indigenous interceptor cost less than $10,000 per unit, a prolonged Chinese campaign of thousands of low-cost munitions would impose massive economic strain. This underscores the urgency to develop and integrate low operational cost, high-volume counter-drone and counter-swarm architectures like an HPM system within the country's Multi-Layered Air Defence System in order to create a sustaining security model that enables India to defend its air littoral against a peer adversary like China.

Economic Breakdown to understand the advantage of possessing an HPM system (Analysis)

The following analysis is an attempt to compare the cost of intercepting drone attacks that were carried out during the most recent two major conflicts, “Ukraine-Russia” and “Iran-Israel” and using traditional air-defence systems against a hypothetical scenario where in case if HPM system were deployed.

(Cost figures are in US dollars)

Iran - Israel conflict (April 2024)

Drones used: 200 Shahed-136 and Shahed-131 swarm attack drones from Iran into Israel's airspace. (Avg cost of Shahed-136 and Shahed-131 drones is roughly $27,000-$35,000 per unit) (Nông, 2025) along with hundreds of FPV drones (Avg cost of commercial FPV drones is $500 -$2000 per unit).

Interceptor used: Almost all drones were shot down by a combination of fighter aircraft F-35 & F-15EX (Avg cost of Flight Hour $29,000 to $42,000) with AIM - 9X and AIM-120 costing separately around $450,000 and $1.37 million separately (*Defense Express*, 2023) (WION, 2025b), Israel's Muli-layer air defence system that are used for Drone and UAV interception such as the Iron Beam (operational cost of $10-$20 per interception, although It is capable of intercepting only one target at a time) Iron Dome (operational cost $40k - $150K per interception) and David's Sling (operational cost $700k-1M per interception) and naval SAMs costing $4 million per unit (Trevithick, 2024).

So the average cost of intercepting and neutralising a drone would be around $ 300,000 to $500,000, assuming multiple defence fronts are a play. Therefore, the cost of defending against only 200 Shahed drones would be at least 200 × $300,000 = $60 million. Average Cost of intercepting a drone using HPM is just the electrical cost, which comes to $0.05. Hypothetically, if an HPM system were deployed on multiple fronts against such attacks, the cost of neutralising 200 drones all with an HPM system would be 200 × $0.05 = $10.00

Ukraine-Russia Conflict (2024-2025*)

Drones used: Roughly 15,000 Shahed-136 drones fired at military and civilian Ukrainian infrastructure over the 2024-2025 period (Anokhin & Faragasso, 2025). Interceptor Used: Ukrainian air defence relies on Stinger missiles, guns and other forms of mobile SAMs. The average cost of 1 Stinger Missile is $120,000-$150,000 (Ukraintoday.org, 2024). Based on radar detection and tracking, Ukraine's Air Defence system was able to intercept almost 91% of those Shahed drones (Defence News, 2024). But the interception-to-target ratio is below 1:1 since multiple missiles are required to be able to guarantee a kill. Therefore, the lowest average intercept cost would be roughly $70,000 to $100,000 per drone (primarily Stinger and gun ammunition, with some SAM missile use). Therefore, the cost of neutralizing 1000 Shahed drones would come to: 1000 × $100,000 = $100 million. HPM systems such as the Eprius Leonidas operational cost per shot of $0.05 (UNITED24 Media, 2025). Therefore, the cost of operation against these drones would be 1000 × $0.05 = $50.00, $100 million using traditional kinetic AD systems vs. $50 Operational Cost of HPM, highlighting the economic advantage of DEW HPM weapons.

Conclusion

This assessment is done to understand the advantage an HPM system can bring into a country's air defence layer. There are other additional cost factors in a conflict for both sides, such as the operational cost of the Radar system, communication system, man-power etc. But with cheap swarm drone attacks becoming a reality, the inclusion of other cost factors of conflict would only add to the asymmetric gap drone attacks present against traditional kinetic and non-kinetic systems. From this illustrative case alone, the total cost of traditional drone interception systems exceeds roughly $250 million, while the HPM alternative would cost less than $220-250. This represents a cost reduction factor of over "one million to one".

Even if we take into account the procurement cost of a typical DEW-HPM system (e.g, IFPC-HPM; the cost comes to around $15-$25 million per unit), inclusion of a network of such a system into India's air defence layer would essentially create a formidable electromagnetic field against any kinda swarm attack. This will give the country a massive comparative advantage against its adversaries on all sides.

In a prolonged military operation such as the Ukraine-Russia conflict, there have been tens of thousands of drone attacks by either side, with the number of drones used getting larger each time. The economic pressure on the defender using kinetic interceptors is simply unsustainable in such longer runs. Missile stockpiles can deplete at a rate faster than the industries can produce. If such a situation were to prevail for India, even a conflict/operation extending even 2 months could prove to be lethal for the country's economy and thereby its security. The DEW-HPM system turns the tide in this economic asymmetry of drone warfare, allowing the country to maintain long-term strategic advantage. On 19th May 2026, during the 3rd edition of the defence ministry's ADITI initiative, the Indian Navy signed a contract with Tonbo Imaging for acquiring HPM systems. Although the nature of the contract remains a secret, such contracts of procurement and acquisition need to be done across all three domains within the Indian Army. It is certain to say that the only rational counter to drone warfare is Direct Energy Weapons like the HPM system.

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