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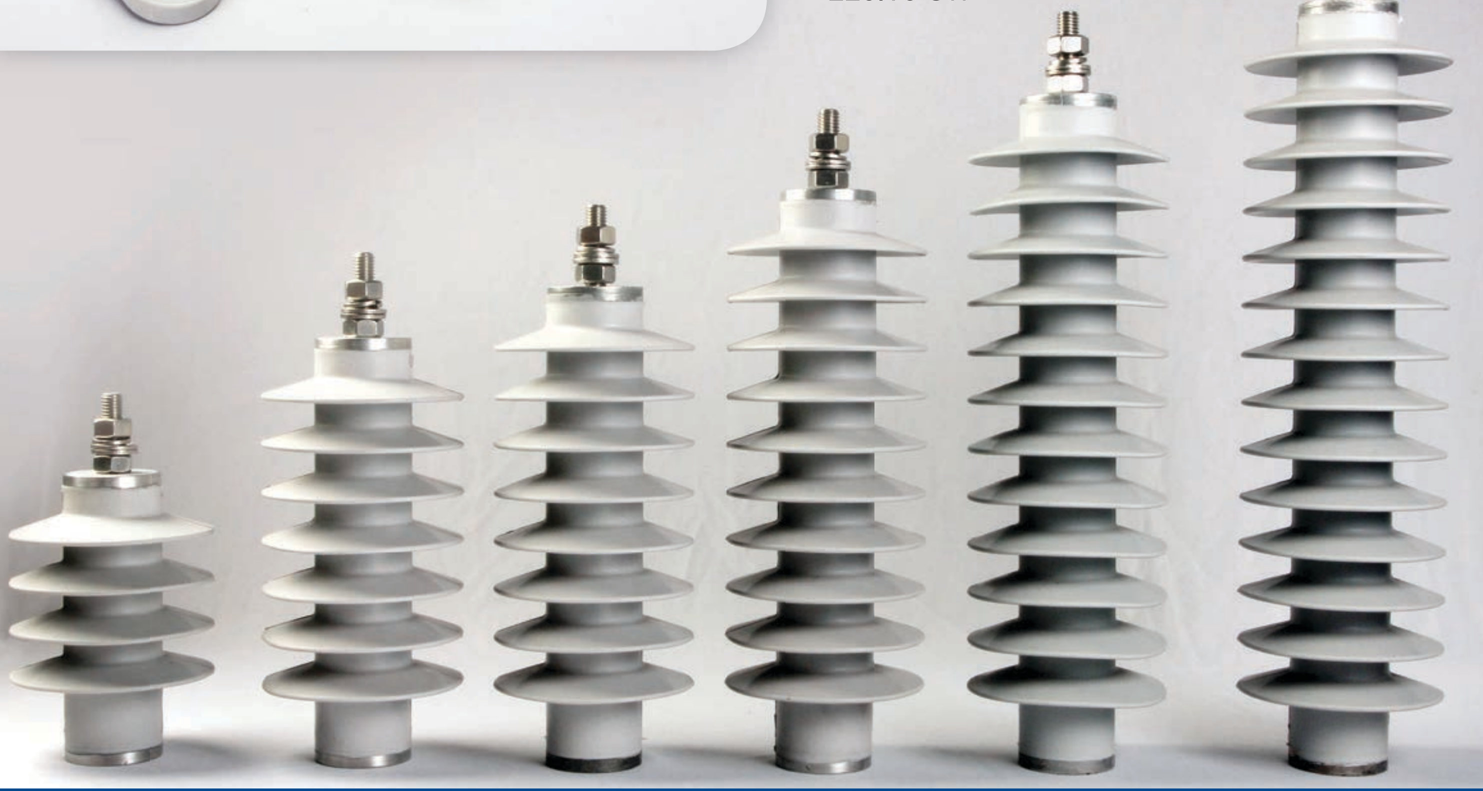
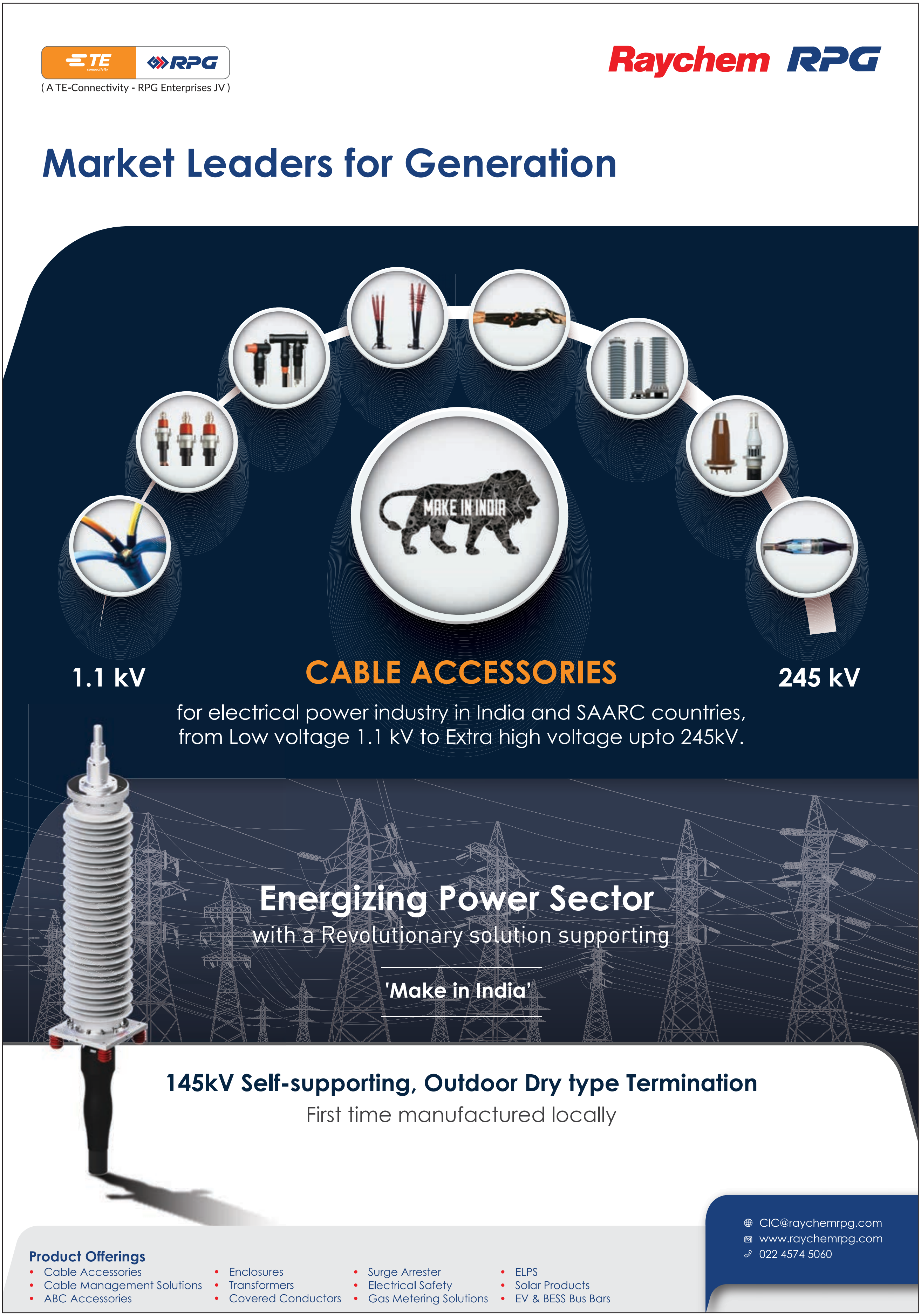
SURGE ARRESTERS: A COMPREHENSIVE OUTLOOK

OTHER STORIES:

- **CASE STUDY:** Advanced Condition Monitoring Techniques for Surge Arresters
- **INSIGHT:** Challenges faced in Integrating Inverter Based Resources
- **SPECIAL REPORT:** India's total installed RE capacity reaches 220.10 GW





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FROM THE PRESIDENT'S DESK

Dear Readers,

India's power sector has undergone a profound transformation over the past few decades. From battling shortages and inefficiencies in the 1990s to now leading ambitious global renewable and smart grid missions, the journey has been nothing short of remarkable. At the heart of this evolution lies the resilience and innovation of India's electrical and electronics industry, which has steadily transitioned from being a component supplier to becoming a formidable force on the global energy stage.

The Rise of India's Electrical Manufacturing Ecosystem

India today is not only self-sufficient in most categories of electrical equipment but also a reliable supplier to over 100 countries. Indian products – from transformers and switchgear to energy metres and control systems – are now seen as robust, cost-effective, and technologically competitive. Behind this success lies decades of focused efforts by Indian manufacturers, their R&D capabilities and policy reforms supporting Make in India, standards harmonisation, and ease of doing business.

At IEEMA, we are proud to have contributed to shaping this transformation. Our members, ranging from large multinationals to MSMEs, have embraced digitalisation, sustainability, and quality with vigour. The increasing adoption of Indian standards abroad and growing recognition of Indian testing and certification capabilities are signs that India is moving from "competing on cost" to "competing on quality and innovation".

However, being a major exporter is not the summit of ambition – it is the base camp. The next frontier is about thought leadership. We must now shape the future of global energy systems, not just participate in them.

This means India must:

- Lead in standards formulation: Indian experts must actively contribute to international standard-setting bodies like IEC, IEEE, embedding Indian conditions, innovations, and sustainability approaches into global frameworks.
- Export innovation, not just equipment: Indian firms are developing cutting-edge solutions in energy analytics and AI-driven grid diagnostics. These innovations should be scaled globally, especially to emerging economies with similar challenges.
- India can support the UK, Europe Africa, Southeast Asia, and Latin America not just through products but via turnkey solutions, services, helping in capacity building and becoming a true energy development partner.

IEEMA is fully committed to this global vision. Through strategic collaborations, export promotion initiatives, trade fairs like ELECRAMA, and deeper engagement with BIS and global technical committees, we are building the foundation for India to be recognised not only as a supplier but as a standard-setter.

We also believe in public-private synergy. Our partnership with the Government of India in aligning trade and technical diplomacy is essential in ensuring Indian interests are reflected in global rules of the game.

This is a defining moment. As the world transitions towards net-zero, decentralisation, and digital energy ecosystems, India has the talent, experience, and manufacturing strength to lead. But leadership demands courage, consistency, and collaboration.

Let us embrace this opportunity – not just to export goods, but to export trust, standards, and innovation.

The future is not something we wait for – it is something we shape. Let us shape it together.

SUNIL SINGHVI

Dear Readers,

India has achieved a total installed renewable energy capacity of 220.10 GW, an advanced step towards achieving our 500 GW target of non-fossil fuel energy by 2030. The industry together recorded a robust annual capacity addition of 29.52 GW, with solar energy as a major contributor, followed by other sources.

Our total installed solar capacity now stands at 105.65 GW, including 81.01 GW from ground-mounted installations, 17.02 GW from rooftop solar, 2.87 GW from solar components of hybrid projects, and 4.74 GW from off-grid systems. The total cumulative installed wind capacity in India is now at 50.04 GW. The rapid growth of renewable energy in India represents a notable milestone, and its firm commitment to achieving its *"Panchamrit"* goals. It enables us to scale up quickly and help in achieving our *'Viksit Bharat 2047'* vision. But with a developing Bharat, we also need to focus on a *'Surakshit Bharat'*.

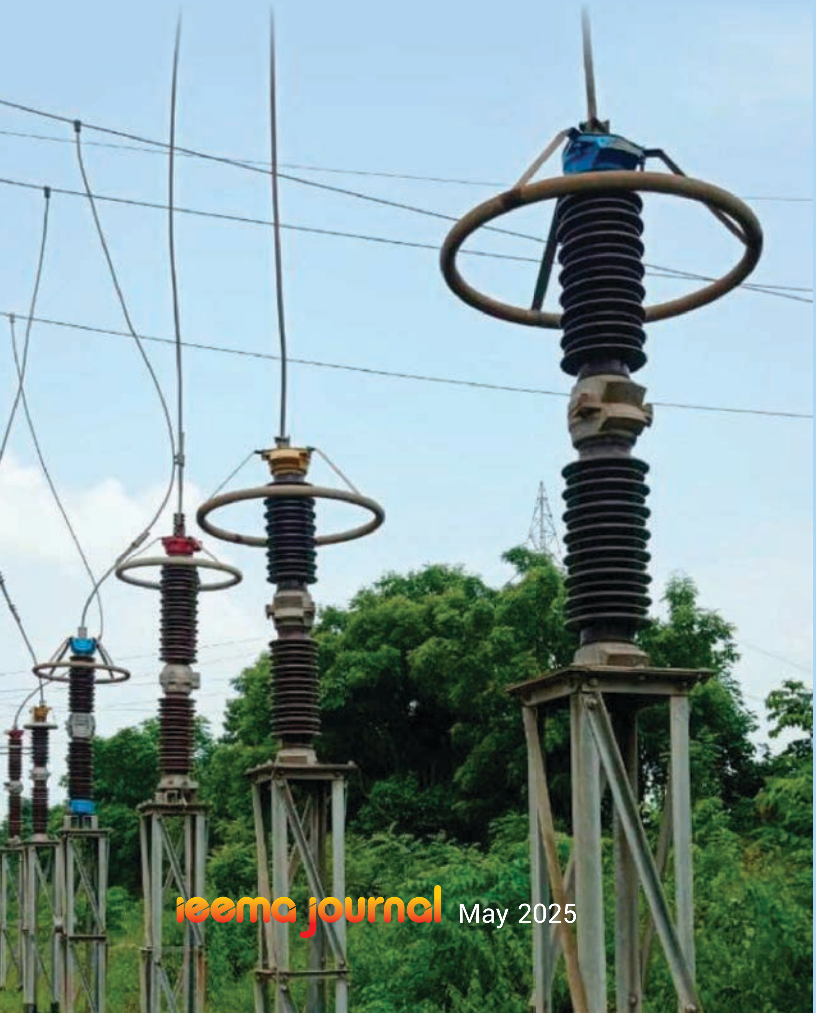
Strengthening our endeavour to promote quality, safety, and reliability, we at IEEMA are continuing to build focus on these three aspects. IEEMA's quality cell is undertaking several new initiatives for this. IEEMA is partnering with IIT-Kharagpur for a certificate course in Reliability Engineering for electrical industry professionals. IEEMA is also joining hand with the Quality Council of India for a lean certification programme for its MSME members.

To build awareness on safe and reliable practices in electrical installations and usage and promote technologies for managing mishaps, IEEMA is promoting electrical safety campaign across cities through Electrical Fire Safety Conclaves. We recently hosted the Electrical Fire Safety Conclave in Mumbai, with conclaves in Delhi, Bengaluru and Kolkata to follow.

Like I mentioned in my last message, IEEMA is gearing up to grow its thought leadership focus on key topics this year. We will be hosting the state conclaves to further strengthen our regional focus, with the NorthEast Conclave planned in June. We will also be organising the T&D Conclave in Delhi and MEP Consultant Meet in Kochi in June, respectively – stay tuned for details on these are more.

CHARU MATHUR

Navigating Headwinds and Harnessing Opportunities: A Comprehensive Outlook of the Surge Arrester Market Segment in India



In the Think Tank section of the Cover Story, **IEEMA Surge Arrester Division Chairman, P Kirushnaraj** talks about the evolution of the surge arrester, current market dynamics, the status of raw material and its impact; comments on the influence of market dynamics on the power sector, presents an industry outlook commenting on the opportunities amidst challenges; to remark on the role of policies, followed by enlisting technical challenges all the while presenting solutions and keeping in mind India's global position and trade dynamics.

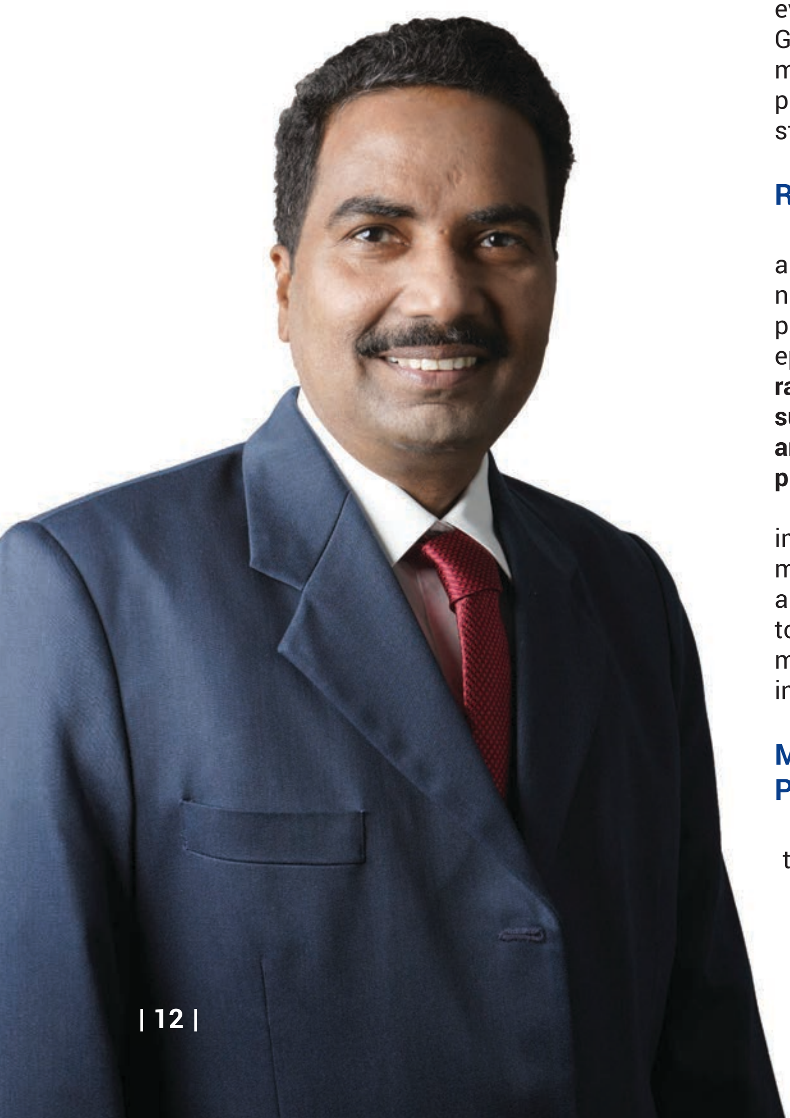
The surge arrester segment, a critical subset of power protection ecosystem, currently stands at a pivotal juncture, marked by technological maturity on one hand and market challenges on the other. Over the past two decades, I have grown alongside this industry, closely observing its evolution from silicon carbide-based gapped arresters to advanced gapless metal oxide technologies, and from traditional porcelain-housed designs to today's dominant polymeric variants. These transitions have not only enhanced performance and reliability but also redefined application engineering across voltage classes. As **Chairman of the Surge Arrester Division of IEEMA,** I take this opportunity to present this comprehensive outlook, grounded in recent statistical trends, IEEMA's industry engagement, and broader global cues.

Performance of the Surge Arrester Segment Over the Last Decade

Over the past decade, the surge arrester segment in India has made significant progress in terms of product innovation, technical evolution, and market penetration. A major development has been the shift from traditional porcelain-based arresters to modern polymeric variants, which now constitute 63% of total market share. This transition reflects the industry's response to the technological changes and increasing demand for surge protection solutions that are better suited to India's diverse and challenging operating environments.

Polymeric arresters offer several clear advantages over their porcelain counterparts: they are lighter, enabling easier handling and installation; fail safe, and feature a hydrophobic silicone rubber surface that resists contamination and improves reliability in polluted or coastal regions. Additionally, their non-fragmenting behaviour during failure minimizes safety risks, and overall contribute to a reduced lifecycle cost, all of which have contributed to their widespread adoption across utility and industrial applications.

Despite this technological advancement and consistent demand, the segment has faced economic headwinds in recent years. The size of the industry has declined from 330 crore to 300 crore in two years, highlighting increasing pricing pressure and lower unit realisation. This trend points to a key structural issue: while production volumes have remained stable, margins have narrowed significantly. The path forward will require a greater focus on value-added offerings, cost efficiencies and product differentiation through innovation if the industry is to sustain growth and profitability in a competitive landscape.



Current Demand and Supply Scenario

The surge arrester market segment in India has witnessed a clear shift in its demand landscape, with the domestic market now accounting for 72% of total sales, up from 57% previously. This notable increase reflects sustained infrastructure development, rural electrification efforts, and a broader push by utilities to strengthen grid resilience and safety. The integration of renewable energy sources, particularly in semi-urban and underserved regions, has further driven demand for reliable protection systems, reinforcing the domestic market as a central growth engine.

Conversely, the export share has declined from 43% to 28%, highlighting mounting challenges in global markets. The drop may be attributed to a combination of factors — including heightened international competition, pricing pressure, quality expectations and changing sourcing patterns in key regions. This contraction in export activity has played a significant role in constraining revenues, even as overall production volumes remain steady. Going forward, it will be essential for the arrester manufactures to rebalance its focus, reinforcing its position in global markets while capitalizing on the steady momentum within India.

Raw Material Status and Impact

Raw materials constitute a major portion of arrester manufacturing costs. With 63% of production now comprising polymeric surge arresters, high-performance rubber compounds, metal oxides, and epoxy resins are in constant demand. Unfortunately, **raw material volatility, driven by geopolitical supply chain disruptions, currency fluctuations, and international freight issues has eroded cost predictability.**

Manufacturers are increasingly reliant on imported components, particularly for high-grade metal oxides, which affects both pricing flexibility and supply chain agility. There is an urgent need to bolster domestic production of these strategic materials through government-backed R&D and industrial collaboration.

Market Dynamics and Influence on the Power Sector

India's power sector is undergoing a transformation with the advent of smart grids, renewable integration, and increasing emphasis on automation. Surge arresters are indispensable in these ecosystems for ensuring reliability and safeguarding infrastructure. However, industry dynamics are being affected by aggressive price-based competition, uneven adoption of quality standards, and procurement practices that still prioritize cost over lifecycle value.

In addition, the weak export performance raises concerns about our global competitiveness. To regain momentum, we must align more closely with international standards and expand our presence in emerging markets as a first step.

Industry Outlook: Opportunities Amidst Challenges

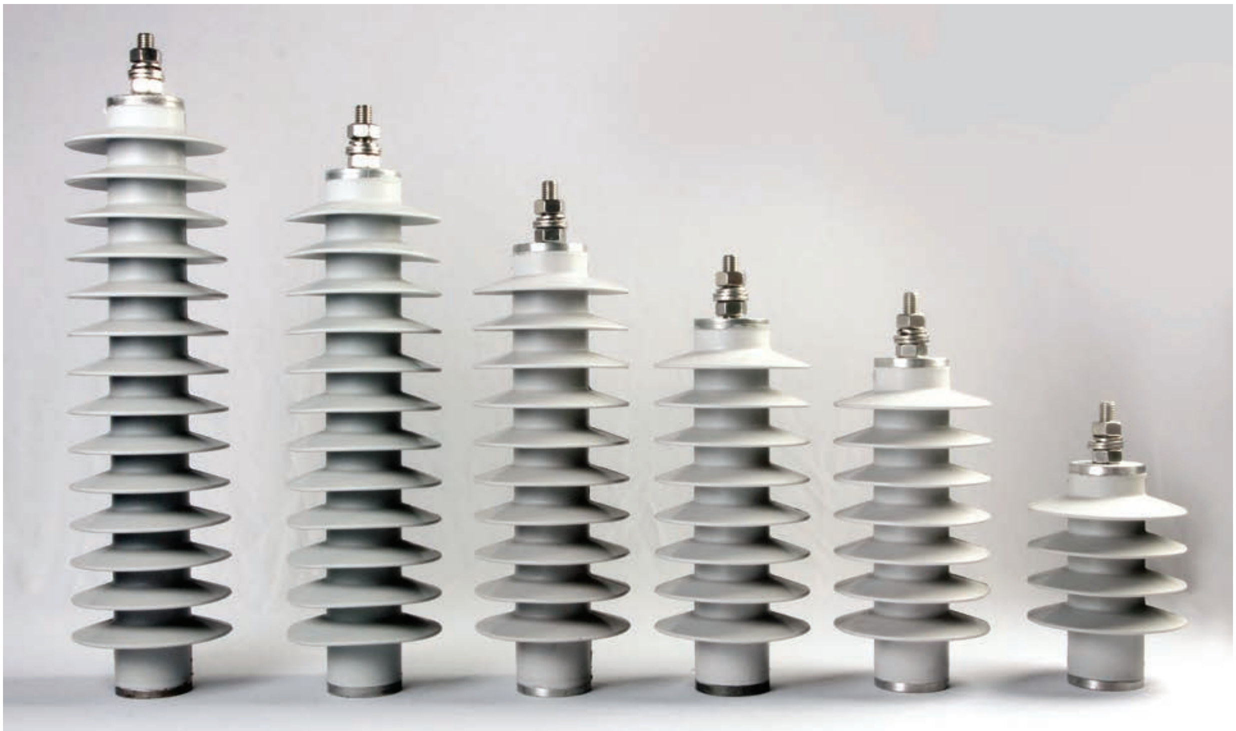
While short-term revenue pressures persist, the **medium to long-term outlook remains positive.** Encouragingly, the increase in domestic sales signals strong underlying market potential. The surge in domestic demand is expected to continue, especially with infrastructure initiatives such as the **Revamped Distribution Sector Scheme (RDSS), 500 GW Renewal Energy Capacity by 2030, Gati Shakti, Smart cities,** and **green energy corridors.**

According to a report by Fortune Business Insights, the global surge arrester market was valued at USD 1.97 billion in 2023 and is projected to reach USD 2.06 billion in 2024 and USD 2.99 billion by 2032, growing at a **CAGR of 4.8%** during the forecast period. This steady global growth presents significant export opportunities for Indian manufacturers, provided they can enhance product quality, competitiveness, and acquire globally recognized certifications.

Emerging applications such as renewables, data centres, and modern building infrastructure are driving demand for low voltage Surge Protection Devices (SPD), Transient Voltage Surge Suppressors (TVSS), arresters for gas insulated substations (GIS) and separable connectors with plug-in surge arresters. These products are currently dominated by imports, presenting a clear opportunity for domestic players to localize manufacturing and innovate.

Moreover, the adoption of transmission line arresters by major utilities across India, in conjunction with the impending governing standard IEC PT 60099-11, which is currently under development, is projected to expand market growth. Indian manufacturers have the opportunity to position themselves as technical solution providers by developing in-house capabilities for **"Transmission Line Lightning Performance Analysis"** and offering expert recommendations on arrester type, optimal location, and quantity to deployed as a complete turnkey solution for transmission line protection.

To fully capitalize on these opportunities, the industry must focus on value-added solutions, robust product differentiation, and integration of digital features. Strategic investments in R&D, supported by forward-looking policies, will be instrumental in enhancing India's competitiveness in the global surge protection market.



Policy Suggestions and Industry Needs

IEEMA has consistently advocated for policies that encourage local manufacturing under the Make in India initiative. We propose the following:

- Incentives for localizing critical raw material production, reducing import dependency.
- R&D funding for next-generation arrester technologies, especially for high-voltage and smart grid applications.
- Export promotion schemes tailored for electrical protection equipment.
- Standardization of procurement policies across utilities to avoid unhealthy price competition and promote performance-based selection.
- Incentivized replacement programs for aging and underperforming arresters in the field.
- Strengthen CPRI and other regional testing infrastructure to handle newer and more advanced product variants.

Technical Challenges and Potential Solutions

Surge arresters face several technical challenges, including the need for high energy handling, thermal stability, and precise coordination with system insulation. Environmental factors like UV exposure, pollution, and moisture further accelerate aging and degradation. The increasing complexity of applications, such as in transmission lines and renewable systems, adds to the difficulty of selecting the appropriate arrester type, rating, and installation location.

- To address these challenges, manufacturers are progressively adopting advanced metal oxide varistors (MOVs), line disconnector mechanisms, and composite housings with enhanced environmental resistance. Smart surge arresters with IoT-based sensors, enable real-time monitoring of leakage current, temperature, and surge events, supporting predictive maintenance.
- Tools for lightning performance analysis and insulation coordination studies help optimize arrester deployment, while plug-in arresters along with separable connectors simplify installation in compact setups. These advancements, supported by R&D and digital integration, are essential for enhancing system reliability and lifecycle performance.

Technological Innovations on the Horizon

Innovation is vital for the sector's advancement. The next frontier lies in:

- Nano-zinc oxide materials for improved varistor performance.
- Advanced silicone composites for extended thermal and UV resistance.
- Integrated condition monitoring systems that enable remote diagnostics.
- Development of multi-functional surge protection devices compatible with solar, wind, and battery storage systems.

These advancements not only enhance reliability but also help arresters become smarter and more responsive, aligned with evolving grid needs.

Digitisation in Surge Arrester Market Segment

Digital adoption in surge arresters is still in its early stages but gaining ground. Several utilities are piloting smart surge counters and IoT-based solutions. However, adoption remains limited due to cost and awareness constraints.

As utilities digitize their asset base, digitally enabled surge arresters will be essential for real-time monitoring and predictive failure alerts. A push toward standardizing these features in tender specifications could significantly accelerate adoption.

India's Global Position and Trade Dynamics

India has historically been a strong exporter of surge arresters, especially to Africa, Southeast Asia, Europe and the Middle East. The recent dip in exports is concerning but can be reversed with concerted efforts to improve product quality, reduce costs through efficiency, and strengthen trade partnerships. We need to explore free trade agreements and export financing mechanisms to reclaim our global standing.

Additional Industry Concerns

One crucial aspect not frequently addressed is the lack of structured end-of-life management for surge arresters. Many utilities continue using arresters well beyond their safe operational life, posing systemic risks. There is a need for awareness campaigns and guidelines on periodic replacement and testing.

Conclusion

In closing, while the surge arrester market segment is currently navigating through a phase of revenue compression and export headwinds, the fundamentals remain strong. By focusing on quality, innovation, and collaboration between stakeholders, the segment can emerge more resilient and globally competitive.

IEEMA remains committed to supporting this transformation through advocacy, standardization, and knowledge sharing.

P Kirushnaraj is also Director-R&D, Global Business Support, Sicame Group.

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Surge Arresters for the Protection of Electrical Equipment

Guest author **O. Balagangadhar**, a senior member of the IEEMA Surge Arresters division, delves into the growing need of surge arresters, its historical types, technological genesis, special application of zinc oxide arresters and availability of raw materials.

The electrical power system is exposed to different overvoltages due to lightning, switching surges and temporary overvoltages. Lightning surge voltages that travel to the line entrance of a station are caused either by a lightning flash terminating on the overhead shield wire or structure with a subsequent back flash over to the phase conductor or a lightning flash terminating on the phase conductor. Switching action in the system causes the switching overvoltages to last for milliseconds. Switching over voltages increases with an increase in the operating voltage of the system. The insulation of the equipment is not capable of withstanding lightning and switching over voltages.

The duration of overvoltages varies from microseconds to seconds, depending upon the type of surges. Under these overvoltage conditions, the insulation of the power system/equipment could undergo stresses that could lead to catastrophic failure. Hence, it is essential that the power system equipment be protected from these over voltages at the time of occurrence.

Introduction

Surge arresters are used to protect electrical power system equipment from lightning and switching over voltages. The surge arrester has to always limit the voltage across the terminals of the equipment to be protected below its insulation withstand voltage. Up to 132 kV, the system insulation has to be designed to withstand primarily lightning surges. Above 132 kV, both lightning and switching surges have to be considered. For EHV & UHV systems, switching over voltages in combination with insulator contamination becomes the predominant factor in the insulator design.

Historical Progress of Arrester Technology

Since the inception period of power system initially around 1930, simple spark gaps were used to divert the overvoltages due to lightning and switching surges. During 1940 series gaps with lead oxide pellets housed in glass bushings were used. Thereafter during 1950 passive gap type surge arresters having series gaps with silicone carbide non linear resistors housed in porcelain bushings were started. During 1960 current limiting gap type surge arresters with series gaps with magnetic blow out coil and silicon carbide nonlinear resistors designed by E. C. Sakshaug, GE, USA were started around the globe including India.

At that time, it was believed that the technology of surge arresters has reached the saturation limit. During 1970 Matsuoka of Matsushita Wireless Electric Company, Japan had invented zinc oxide (ZnO) with other metallic oxides like bismuth oxide, antimony trioxide, cobalt oxide, nickel oxide, chromium oxide and other dopants, suitable for the manufacture of metal oxide varistors. The development of ZnO based ceramic nonlinear resistors is treated as a major breakthrough in power system protection. By 1980 the arrester technology was totally changed to metal oxide arresters with porcelain housings. Subsequently during early 2000's metal oxide arresters with silicone polymer housing were introduced around the globe. This change over to polymer housed surge arresters was due to pollution related problems.

Seismic Performance of Porcelain

Resonant frequencies can cause immense dynamic forces and due to its weight and brittle nature, porcelain is more susceptible to destructive harmonic frequencies. Porcelain's brittleness makes it prone to cracking and failure under dynamic forces, especially at resonant frequencies during earthquakes. For application under seismic conditions, the high stress areas are to be identified using applicable software (i.e. Finite Element Analysis FEM) & also the bending stress to be calculated accordingly. Seismic performance of porcelain under seismic conditions is possible through weight reduction methods but the same are not feasible & not economical methods. Since weight is a key factor when calculating the force that goes into the equipment during seismic event, the challenge is to optimize the design and maximize the strength to weight ratio.

Seal Pumping in Porcelain Housed Surge Arresters

Moisture ingress in porcelain-housed surge arresters is the single biggest cause of failure of this type of surge arrester. Metal oxide discs do not absorb moisture, but the edges will track if energized with moisture present and likely to fail upon impulse. Partial discharge can occur at high voltage stress areas in an arrester when moisture is present. Ozone is a byproduct of partial discharge. Ozone will cause tracking along the side of the disc and may also change the electrical characteristics of the metal oxide blocks.

Porcelain Arresters Vs Polymer Arresters

If the pressure relief rating of the porcelain arrester is exceeded, it may explode violently, expelling porcelain and internal components and potentially damaging the equipment and injuring personnel in the substation. When porcelain arrester vents, the housing becomes weak. The claimed pressure relief capability of porcelain-housed arresters is only for first venting. The venting of a shorted arrester results in a circuit breaker operation. Most utilities will automatically reclose at least once into a fault.

This causes the porcelain arresters to explode. The failed polymer-housed surge arrester can be reclosed a number of times without shattering.

A porcelain surface has hydrophilic properties and the silicone polymer has hydrophobic properties. In high pollution conditions, polymer insulation electric strength is greater than in porcelain insulators.

Polymer Arresters – In Cage Design

Zinc oxide blocks of each unit of the arrester with spacers are assembled in a cage of eight boron-free ECR grade FRP rods to form an open cage design in between end terminals under axial pre-compression. The pre-compressed unit stack is crimped on the end terminals and on the spacers at high crimping force to hold the cage for a tensile force of 8T (minimum). The cage construction is injection moulded covering all the internal parts, including end terminals, in a single shot using HTV silicone rubber from Wacker. Thus, the module is sealed throughout the length from the top terminal to the bottom terminal and from outside till the surface of the blocks, making the arrester of fully moulded, voidless construction, leaving no way for the diffusion of moisture and no condensation on the internal parts in any form that is detrimental to the arrester performance.

In the case of a fully moulded cage construction having no voids, there is no separate sealing system, no separate pressure release arrangement and no part of the internal components is exposed. In case of an overload or short circuit, the arc escapes directly through the silicone polymer housing, so there is no possibility of any internal parts being ejected and damaging other equipment. The silicone rubber should have high track, erosion and UV radiation resistance guaranteeing long-term stability of the housing material.

Arresters for Fail Safe Protection- Cage Design

This cage construction has no voids and no chance for radial discharges and there is no separate sealing system and no separate pressure release arrangement. In case of an overload or a short circuit, the arc escapes directly through the silicone polymer housing by burning and tearing of the housing. No possibility of any internal parts being ejected and damaging other equipment during a short circuit. No way for the diffusion of moisture as it is a fully moulded construction. No condensation on the internal parts, in any form that is detrimental to the arrester performance. Good pollution performance due to a hydrophobic nature with excellent dielectric strength. Exceptional tolerance to seismic disturbance. Low weight and resistant to transport damages and careless handling.

Performance Under Pollution

1) Problems arising from pollution were the reason to change over to polymer-housed surge arresters.
2) The hydrophobic surface of polymeric housing considerably reduces the problem of pollution.
3) The surface current along one unit of high external conductivity commuting to the MO column of next unit heating the MO resistors of this unit.
4) The best way to avoid partial heating of individual units is to apply single-unit arresters wherever possible or to reduce the number of units per column.

Polymer Arresters – In Tube Design

For ultra-high voltage arresters, the tube design is adopted for the mechanical consideration to meet a total height of 8M per arrester column. Primarily, the number of units per column of the arrester is to be reduced for proper distribution of voltage across units. With the reduction of units per arrester column along with the proper design of the grading ring, which considers the overall diameter, height and size of pipes used for the grading ring, near-uniform voltage distribution can be achieved.

Moisture ingress is the single cause of arrester failure worldwide—both for porcelain-housed arresters and for hollow-core polymeric arresters. Moisture is drawn inside the arrester due to the difference in pressure between the internal and external arresters, and this pumping mechanism tends to draw in moist air. The relative humidity on the inside reaches the same level as outside. At some point the temperature of the moist internal volume drops below the dew point, and moisture condenses along the arrester's electrically stressed internal components. This leads to dry band arcing and dielectric tracking along the wetted surfaces and will eventually result in a short circuit of the unit. Utmost care is taken for the sealing of the pressure release arrangement provided on both ends of the hollow core insulator.

Transmission Line Arresters

Overhead transmission lines are the most vulnerable for lightning strokes. More than 50 percent of the electrical faults of overhead lines are known to be caused by lightning induced voltages reaching the tower and causing the line insulator to flashover, resulting in an interruption. Back flash over occurs during the lightning discharge current, flowing through the tower and due to tower footing impedance producing potential differences across the line insulator. Back flash over is most prevalent when the tower footing impedance is high. Installation of ZnO arresters across the line insulators (at frequent intervals) would minimize and or eliminate the possibilities of insulation flashover.

Special Applications of ZnO Surge Arresters

A. Arresters for Transformer Neutrals

- One of the most widely used special applications of arresters is for the protection of transformer neutrals.
- Each unearthed neutral brought out through a bushing should be protected against lighting and switching over voltages by an arrester.

B. Arresters Between Phases

- Significant over voltages between the phase terminals of transformers or reactors may occur when a reactor or a reactive load transformer is switched off.
- If such switching operations are expected, surge arresters should be applied between phases in addition to those across phase-to-earth.

C. Arresters for Rotating Machines

- Superior characteristics of ZnO arresters have become more valuable in motor and generator protection.
- Special arresters are often used for rotating machines and the requirements are defined and agreed upon between the manufacturer and user.
- For generator arresters, attention should be paid to their pressure relief performance as the short-circuit currents could be appreciably higher.

D. Arresters for Capacitor Banks

- Shunt capacitor banks are used to an increasing extent at all voltage levels to avoid the transfer of reactive power, better use of the existing power system for improved voltage stability and compensate for reactive loads.
- In case of breaker-switched capacitor banks, the probability of high transients associated with capacitor switching increases, as many banks are switched daily.

ZnO Arresters at Capacitor Banks are Necessary

- To prevent capacitor failures at a breaker restrikes.
- To limit the risk from repeated breaker restrikes.
- To prolong the service life of the capacitors by limiting high over voltages.
- To serve as an 'insurance' against unforeseen resonance conditions which otherwise would lead to capacitor failures.
- For overall limitation of transients related to capacitor bank switching which can be transferred further in the system and cause disturbances in sensitive equipment.
- To serve as protection against lightning for capacitor banks connected to lines.

Raw Material Scenario

Antimony metal, from which antimony trioxide is made, is procured from China. It is an important raw material to produce zinc oxide blocks. China, which supplies 60 percent of the global demand, has banned the export of antimony. Globally, antimony ore is available in negligible quantities. It is uneconomical to process the quantities available in those few countries. Notably, there is no supply of antimony trioxide, so currently, the manufacture of zinc oxide blocks has come to a standstill.

Chinese Governmental Support

There are multiple manufacturers of zinc oxide blocks in China, as all the raw materials are available in the same country, and the manufacturing plant of zinc oxide blocks is readily accessible along with the testing equipment. The finished zinc oxide blocks are allowed to be exported by China, and exporters of zinc oxide blocks are eligible to claim an 18 percent export benefit.

The Chinese state-owned industry was started by the Chinese government in collaboration with Hitachi. Technical experts were sent to Hitachi to absorb the technology for the manufacture of zinc oxide blocks. A detailed document was prepared by the experts in the Chinese language. This document was shared with start-up industries to initiate the manufacture of ZnO blocks while experts were asked to help them technically.

The Chinese government's initiative to cull technical knowledge in collaboration with Hitachi to prepare a full-fledged document detailing the composition, process, and testing as per the prevailing IEC-60099-4 for metal oxide arresters has helped many industries to start manufacturing zinc oxide blocks.

As such, the technology sharing document is not available in India, and the manufacturers of zinc oxide blocks are limited to two in number. Nobody is interested in venturing into the manufacturing of zinc oxide blocks, as at present the investment in a ZnO manufacturing plant and equipment is not economically feasible.

ABOUT THE AUTHOR

The author, **O. Balagangadhar** is a first-generation technocrat and the Managing Director of Oblum Electrical Industries Private Limited. Since founding the company in 1970, he has led it with a strong focus on innovation and industry standards.

Advanced Condition Monitoring Techniques for Surge Arrester: Enhancing Reliability and Predictive Maintenance in Power Systems

P Kirushnaraj, Director-R&D, Global Business Support, Sicame Group presents a technical paper on enhanced reliability and predictive maintenance achieved in power systems through the advanced condition monitoring techniques used for surge arresters.

Surge arresters represent a vital component within power systems, as their function is to protect electrical equipment from transient overvoltages. This, in turn, ensures the seamless continuity of power supply. Conventionally, the maintenance of these systems has been a reactive process, entailing periodic inspections that frequently result in unplanned service interruptions and escalated operational expenses. In the context of India's transition towards smart grids and digitalisation, the importance of advanced condition monitoring techniques is increasing. These techniques not only facilitate predictive maintenance, but also serve as a valuable tool to support replacement policy decisions. The provision of real-time data and analysis is instrumental in the assessment of arrester health, with the capability to facilitate the detection of early degradation signs. This proactive approach helps to optimise maintenance schedules, extend asset life and significantly improve the reliability of the power system. The result of this is a more resilient and cost-effective grid.

I. Surge Arresters in the Indian Power Ecosystem

In India's vast and varied power infrastructure, surge arresters are widely deployed in transmission lines, substations, distribution networks and consumer end installations to protect equipment from voltage transients. Electrical systems in India operating at voltages ranging from 11 kV to 765 kV predominantly employed gapless metal oxide surge arresters with polymer-housed arresters gaining preference over porcelain due to their superior performance in polluted environments.

These arresters are exposed to a range of stresses unique to Indian conditions, including high lightning densities in coastal and north-eastern regions, frequent switching in urban grids, contamination from industrial pollution, saline environments and persistent overvoltages in poorly regulated rural feeders. Such stresses contribute to gradual degradation, internal moisture ingress, surface tracking and thermal runaway in arresters.

The asset base is managed by a mix of stakeholders, central and state transmission utilities, independent power producers (IPPs) and distribution companies (DISCOMs), each with varying levels of maintenance infrastructure and practices. While high voltage arresters in transmission systems are often part of planned asset management, arresters at the distribution level, especially in rural or congested urban areas, may suffer from infrequent inspection and data gaps.

The limited field data from Indian utilities suggests that most arrester failures are due to prolonged exposure to overvoltages, improper installation, or aging in polluted conditions. Some utilities have reported an increasing trend of failures during the pre-monsoon and monsoon seasons. These findings underscore the need for improved monitoring and data-driven maintenance strategies to mitigate failure risks and ensure grid reliability. The table I shows the main types of surge arrester failure, their primary causes, and other details for reference.

II. MTTF: A Statistical Abstraction, not a Replacement Policy Tool

Effective surge arrester asset management relies on a balance between condition-based maintenance and strategic replacement decisions. A key metric in this strategy is the Mean Time To Failure (MTTF), which is a statistical measure that represents the expected time before failure occurs for a non-repairable device such as a surge arrester. It is an indication of the average operating time before failure under ideal conditions. The formula for MTTF is

$$MTTF = \frac{1}{Failure\ Rate}$$

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TABLE I. SURGE ARRESTER FAILURE TYPE, CAUSES, MECHANISM AND MANIFESTATION

Failure Type	Primary Cause(s)	Failure Mechanism	Failure Manifestation	Voltage / Current Stress
1. MOV Degradation and Thermal Runaway	Sustained overvoltage, frequent surges, ageing, high ambient temperature, uneven voltage distribution	MOV block heating → V-I drift → leakage current rise	Progressive heating, localized overheating, reduced protection	Sustained overvoltage (1.2–1.5× COV), 100 A–5 kA surges
2. Housing / External Failure	Pollution, surface moisture, low creepage distance, loss of hydrophobicity	Surface tracking or housing puncture, material erosion	Flashover, rupture, visible damage	High surface/ internal electric field
3. Mechanical Induced Failure	Vibration, poor mounting, thermal cycling, transport stress, mechanical fatigue, assembly defects.	Cracks, deformation, MOV column shift, MOV damage.	Structural damage, uneven stress, premature failure	Voltage-independent
4. Short-Circuit Failure	Internal dielectric breakdown, MOV degradation/fragmentation, moisture ingress	Internal arcing, low impedance conductive path formation	Fault current, sudden rupture or venting of the arrester housing	High surge current (kA range), severe faults
5. Unbalanced Electric Field	Poor field grading, nearby metallic objects, sharp edges	Local overstress → partial discharge/ corona	Accelerated ageing, dielectric stress	Localized voltage enhancement
6. Moisture Ingress	Water vapor transmission, poor sealing design or assembly.	Entry of moisture → condensation → reduced insulation → partial discharges → dielectric breakdown	Internal discharge, gradual degradation, flashover	Humid environment, thermal gradients, wet cycles

Here is the case study: A European utility with more than four million arresters in its system began monitoring the annual failure rate of its surge arresters from 1980 and found a failure rate of less than 0.05% for almost the first twenty-five years. However, as most of the arresters exceeded their expected life of 25-30 years, the failure rate increased to an annual rate of 0.8% for the next twenty years. This gives an MTTF of approximately 125 years at 0.8% failure rate.

While MTTF provides a theoretical measure of reliability and it is a common tool for making informed replacement decisions, especially for non-repairable assets. It should be noted that it is a statistical abstraction and does not take into account the real-world factors that affect device aging, such as lightning surges, pollution, thermal cycling and insulation wear. These factors increase the probability of failure as arresters exceed their expected life. Asset management and replacement policies should therefore be based on age-dependent degradation models, field inspections and condition based predictive diagnostics, rather than relying solely on MTTF.

III. Conventional Diagnostic Techniques

A. Field Testing of Surge Arresters

Field testing of surge arresters often used as a measure to evaluate their operational reliability and insulation performance under real or simulated voltage conditions. Both offline and online tests, such as insulation resistance and leakage current measurements at power frequency voltage, are typically performed during scheduled maintenance. While these methods can be time-consuming and labour-intensive, they provide valuable insight into arrester health and support effective

Fig. 1. Typical voltage-current characteristics and test voltage window

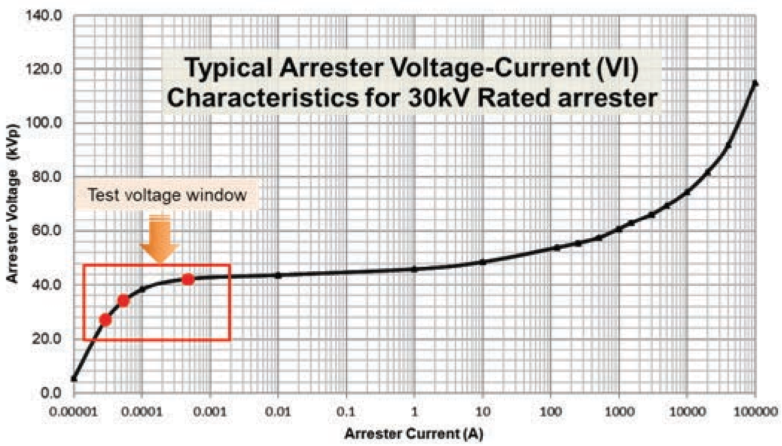


TABLE II. TEST VOLTAGES AND ALLOWABLE LEAKAGE CURRENT LIMITS

Test voltage windows	Test voltage	Power Frequency Voltage in general	Power Frequency Voltage for 30kV Ur	Max. Allowable Leakage Current
Test voltage 1	Phase-to-ground voltage	System voltage / √3	19 kV (27 kVp)	< 500 μA
Test voltage 2	Continuous operating voltage	Uc	24 kV (34 kVp)	< 1 mA
Test voltage 3	Arrester rated voltage	Ur	30 kV (42 kVp)	< 5 mA

condition assessment. However, field crews often face challenges due to a lack of limit values and evaluation techniques.

To address this, a demonstrated field test method is discussed below for a 30kV rated arrester deployed in 33kV system as an example, where three test voltage points are suggested for field testing.

B. Field Test Method 1: Online Measurement of Leakage Current

1) Objective: To measure leakage current (preferably the resistive component) under actual service conditions.
2) Equipment Required: Leakage current sensor/tongue tester, Digital meter, Certified Class 4 electrical safety gloves
3) Procedure:
   - Take safety precautions; testing must be carried out by a qualified electrician.
   - Connect the sensor/tongue tester, digital meter and set it to the correct range.
   - Connect or clamp the sensor/tongue tester to the arrester ground lead.
   - Record the value of the leakage current at the prevailing system voltage.
   - Switch off the meter and remove the tester safely.
   - Correlate the leakage current value and the test voltage points according to the table above (19 kV, 24 kV or 30 kV) and refer to the corresponding leakage current limits for evaluation.

Note: Never disconnect the arrester ground lead while it is energised, as this poses a severe electrocution risk.

C. Field Test Method 2: Off-line Measurement of Leakage current Using Hi-Pot Tester

1) Objective: To simulate voltage conditions in a lab setup for measuring leakage current.
2) Equipment Required: Hi-Pot tester (Suggested Hi-pot tester capability: 1.5 times arrester rating), Leakage current measuring device or tongue tester, Earth stick and Certified Class 4 electrical safety gloves
3) Procedure:
   - Place the earth stick on the HV terminal and connect the arrester and measuring device to the test circuit.
   - Remove the earth stick, secure the area and energise the Hi-Pot tester.
   - Gradually increase the voltage to test voltage 1 or 2 according to the arrester nameplate and measure the leakage current. Test voltage 3 is not recommended as prolonged exposure may heat the arrester.
   - After measurement, switch off all equipment, discharge using the earth rod and dismantle the setup.
   - Correlate the leakage current value with the test voltage points according to the table above.

D. Visual Inspection, Ground Lead Disconnector and Surge Counters

Visual inspection is one of the most common techniques used by utilities to determine the condition of ground lead disconnectors and physical signs of arrester deterioration, such as cracking, tracking, or surface contamination. Although simple, it is highly subjective and may not detect hidden internal faults. Simple surge counters are also widely used to record the number of surge events experienced by an arrester, along with a leakage current display, often with a green and red zone indication. However, they do not provide insight into the condition of the arrester or performance trends over time unless they are fitted with the necessary sensing element and connected to an IOT platform.

E. Infrared (IR) Thermography

IR thermography is a non-invasive method and can be carried out while the system is energised. It is used to detect abnormal surface temperature patterns that may indicate internal damage, moisture ingress or thermal runaway. It requires a set of companion arresters to assess the variations. Arresters with temperature variations between adjacent units above 5°C generally need to be investigated. However, its accuracy can be affected by environmental factors such as ambient temperature, surface emissivity and weather conditions. It may also fail to detect early stage or low intensity internal defects.

F. Limitations of Conventional Diagnostic Techniques

All of the above traditional methods tend to be reactive, periodic and limited in diagnostic depth. They often fail to provide the continuous, real-time insight or early warning needed for predictive maintenance or optimised replacement decisions,

especially for critical high-voltage assets. This limitation underscores the growing need for advanced condition monitoring techniques that enable data-driven asset management.

IV. Advanced Condition Monitoring Techniques

A. Role of metal oxide varistors in surge arresters:

Metal Oxide Varistors (MOVs) are the core protective elements in modern surge arresters. Composed primarily of zinc oxide, MOVs exhibit highly non-linear voltage-current characteristics, offering high resistance under normal operating voltages and transitioning to low resistance during overvoltage events. This allows them to effectively **clamp transient surges** thereby protecting critical equipment. Their fast response time, energy handling capability, and ability to reset after a surge make MOVs essential for reliable and repeatable surge protection in both transmission and distribution systems. The performance of surge arresters depends on MOV. If the characteristic of MOV degrades, the leakage current in the arrester increases. This leakage current is further depending on the applied power frequency voltage, system harmonic content, degree of contamination of the arrester surface, the lightning or switching activity, if any, prior to the measurement, and the temperature at the time of measurement.

The leakage current in surge arresters can be classified into three types:

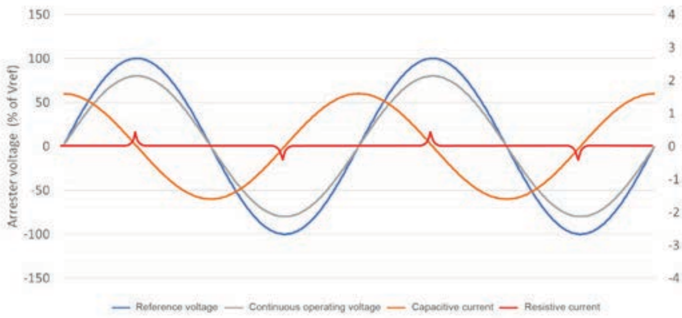
- *Total Leakage Current:* The vector sum of capacitive and resistive currents.
- *Capacitive Current:* Related to the capacitive properties of the arrester, mostly sinusoidal and in quadrature (90° phase shift) with the applied voltage.
- *Resistive Current:* Directly related to the material properties of the arrester and its aging.

Total leakage current: The alternating current (AC) total leakage current is sensitive to the arrester installation as it depends on the stray capacitances. A large change in the resistive current is required to observe a significant change in the total leakage current, so a true analysis of arrester health diagnosis isn't possible by measuring the total leakage current alone, but it is helpful to some extent in fault indication when the total leakage current is predominant of the resistive leakage current.

Capacitive leakage current: The capacitive leakage current in metal-oxide surge arresters is primarily due to the dielectric properties of the non-linear resistor blocks, along with stray capacitances and grading capacitors, if present. Typically ranging from 0.2 mA to 3 mA under normal conditions, this current remains stable over time and is unaffected by arrester ageing. This current is largely stable and sinusoidal, and unlike the resistive component, it does not vary significantly with ageing or deterioration of the arrester's voltage-current characteristics. Consequently, changes in capacitive current do not reflect the health or degradation of the arrester, making it an unsuitable parameter for condition monitoring or fault detection.

Resistive leakage current: The resistive component of the leakage current is a sensitive indicator of changes in the voltage-current characteristic of non-linear metal-oxide resistors. Consequently, the resistive current can be utilised as a diagnostic tool for indicating changes in the condition of metal-oxide arresters in service. The resistive component under AC voltage is defined as the current level at the instant of voltage maximum (dU/dt = 0). The resistive leakage current of a non-linear metal-oxide resistor is typically in the range of 2% to 20% of the capacitive current under normal operating conditions, corresponding to approximately 10~600 µA peak. It is important to note that uncertainties may arise in resistive current measurement when working with long arrester columns that exceed a rating of 72kV. The phenomenon may be attributed to the non-uniform voltage distribution across an arrester, a phenomenon that is primarily influenced by stray capacitances and adjacent equipment.

Fig. 2. Typical voltage-current waveforms



B. Measurement of resistive component of the total leakage current:

There are two main principles that can be used for measurement of resistive component, which can be further divided into different groups as per TEC 37/IEC standard guidelines as detailed below:

<u>Method A</u>: Direct measurement of the resistive leakage current divided into four groups depending on the method of extracting the resistive component of the leakage current:

A1: Using the applied voltage signal as a reference for direct peak resistive current measurement.

A2: Compensating the capacitive component of the leakage current by using a voltage signal.

A3: Compensating the capacitive component of the leakage current without using of a voltage signal.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A4: Compensating the capacitive components of the leakage current by combining the currents of the three phases

Method B: Indirect determination of the resistive component by means of harmonic analysis of the leakage current and divided into three groups:

B1: Third order harmonic analysis of the leakage current

B2: Third order harmonic analysis with compensation for harmonics in the system voltage

B3: First order harmonic analysis of the leakage current

C. Recommended Method for Condition Monitoring Sensor

The availability of a voltage reference signal for measuring the resistive current is more advantageous to obtain less uncertain values for condition monitoring. However, obtaining the voltage reference signal is complicated as it has to be tapped from bushings or potential transformers in the system. As the availability of the voltage signal is complicated for resistive current measurement, options A1 and A2 are good for laboratory measurement but not helpful for field measurement and are therefore excluded.

Method A4 is also excluded as the system requires a three-phase leakage current which is difficult to obtain.

Indirect determination of the resistive component by harmonic analysis of the leakage current is less accurate due to the presence of third harmonics in the system voltage itself. In addition, the harmonics in the voltage can generate capacitive harmonic currents that are comparable in magnitude to the harmonic currents generated by the non-linear resistance of the arrester, so options B1 and B2 are excluded.

Furthermore, option B3 avoids the complications associated with the third harmonics of the system voltage, but it requires a voltage signal to process it and is therefore excluded.

Based on the practical scenario involving field measurement and its use for fault indication, the recommended option is A3. This is a way to make up for a lack of voltage. The basic idea is that a fundamental frequency reference signal is made using information from the leakage current. By adjusting the amplitude and phase angle (which can be done automatically), the reference signal can be made to compensate for the capacitive component of the leakage current. However, there is a problem with harmonics in the voltage. These harmonics create harmonic capacitive currents. These currents can interfere with the resistive component. Also, the compensation signal shows the current in a linear capacitance. This causes the same type of accuracy problem as with method A2. However, given the context, this method is highly recommended.

D. Objectives of the Advanced Condition Monitoring System

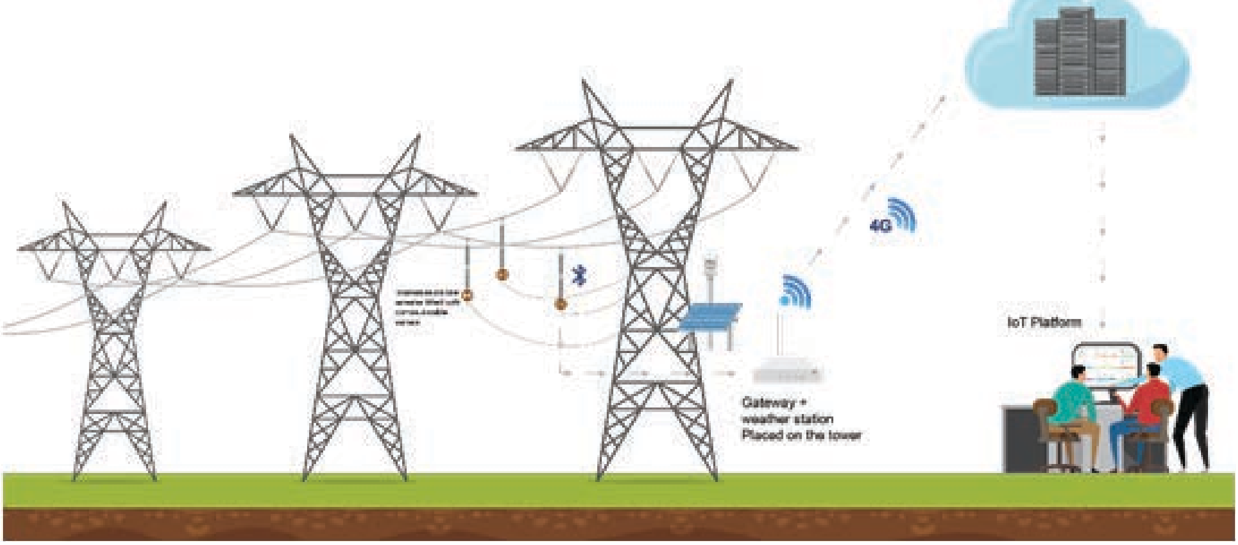
The primary objective of the proposed solution is to improve network reliability and customer satisfaction by reducing the Customer Outage Duration Index (CODI). This can be achieved by:

- Enabling faster fault identification through precise monitoring of surge arresters to quickly locate failure points.
- Minimizing unnecessary equipment stress and operational delays during manual fault detection.
- Improving service availability by reducing outage duration, frequency of feeder interruptions or recloser operations.
- Implement a cost-effective, scalable end-to-end solution tailored to Indian utilities, balancing capital expenditure with long-term operational efficiency.

E. Overview and Description of the Solution

1. Sensor Node: Each sensor node is capable of measuring multiple diagnostic parameters of the arrester, which is mounted directly on the ground terminal /earth electrode of the surge arrester.
   Key features of the sensor node:
   - Arrester Parameters: Monitors surge arrester electrode temperature, the surge events and reference leakage current signal as per recommended option A3 discussed above. Measuring the bottom electrode temperature of a surge arrester can serve as a useful baseline reference against ambient conditions to detect thermal anomalies. A consistent rise in this temperature over time may indicate internal resistive heating due to arrester degradation. When combined with leakage current measurements, it offers more comprehensive insight into the arrester's health.
   - Wireless Communication: Transmits collected data securely to the Gateway for real-time signal processing and cloud integration.
2. Gateway: The gateway serves as a central data aggregation and transmission point. Installed on a tower or pole, it manages communication with multiple sensors. It collects data from all nearby sensor nodes via wireless communication. It securely transmits data to an IoT-enabled cloud platform for advanced analysis and visualization.
3. Weather Station: The deployment of a weather station at appropriate site locations records critical environmental parameters including solar radiation, rain gauge, humidity, and ambient temperature. These inputs are critical for correlating environmental conditions with arrester condition monitoring.
4. Power Supply: Unlike sensor nodes which are powered by battery, the Gateway is energy autonomous, equipped with a solar panel and onboard battery storage for uninterrupted operation in off-grid conditions.

Fig. 3. Architecture of advanced condition monitoring system



V. Measurement, Data Processing and Analysis Techniques

The advanced condition monitoring system is a comprehensive, structured methodology to monitor, process, and analyse surge arrester parameters. This approach is designed to deliver real-time insights into the electrical behaviour of surge arresters and support predictive maintenance strategies. The data handling workflow is divided into three primary stages: raw data acquisition, post-treatment, and analytical interpretation. Collected data is continuously transmitted to a secure, IoT enabled cloud platform for visualization, archiving, and advanced analysis. This real-time digital infrastructure empowers operators to remotely assess surge arrester health, detect early signs of degradation, ageing and enhance system reliability through data driven decision making.

To meet these goals, a practical design approach involves using a dedicated IoT-based sensory device that operates independent of the surge arrester make or type. This allows for retrofitting existing assets and decouples the life cycles of the monitoring device and the arrester. Easily mountable on the ground terminal/electrode, such devices offer flexibility for upgrades and replacements without high overheads, making them especially suitable for diverse Indian network conditions.

VI. Conclusion

The proposed advanced condition monitoring system for surge arresters leverages predictive analytics to shift maintenance strategies from reactive to proactive. By utilizing real-time monitoring data, utilities can implement predictive maintenance practices that help anticipate potential failures before they occur. Artificial Intelligence (AI) and Machine Learning (ML) algorithms play a crucial role in identifying fault patterns and early signs of insulation degradation, enabling timely interventions. The following examples illustrate practical applications of these technologies.

- Gradual or sudden increase in resistive leakage current, accumulated power loss.
- Polarization between positive and negative resistive leakage current.
- Rising arrester temperature, even under normal load conditions.
- Surge event log showing increased activity in short timeframes.
- Measurable change over time in capacitive or resistive characteristics to understand the drift,

These insights are integrated into centralized dashboards, enabling utilities to assess network-wide risk profiles and prioritize maintenance activities. By assigning health index scores based on real-time data and fault pattern analysis, the platform supports informed decision-making to extend asset life and improve operational efficiency. This data-driven approach enhances grid reliability, minimizes downtime, and contributes to a more resilient and optimized power distribution system.

ABOUT THE AUTHOR

The author **P. Kirushnaraj** is a successful engineering manager with consistent contribution in new product introductions (NPD) in the field of surge protection, surge monitoring and diagnosis, composite/polymeric insulators, cable accessories and railways catenary systems, etc. in the energy sector. He is also Chairman Surge Arrester Division, IEEMA.

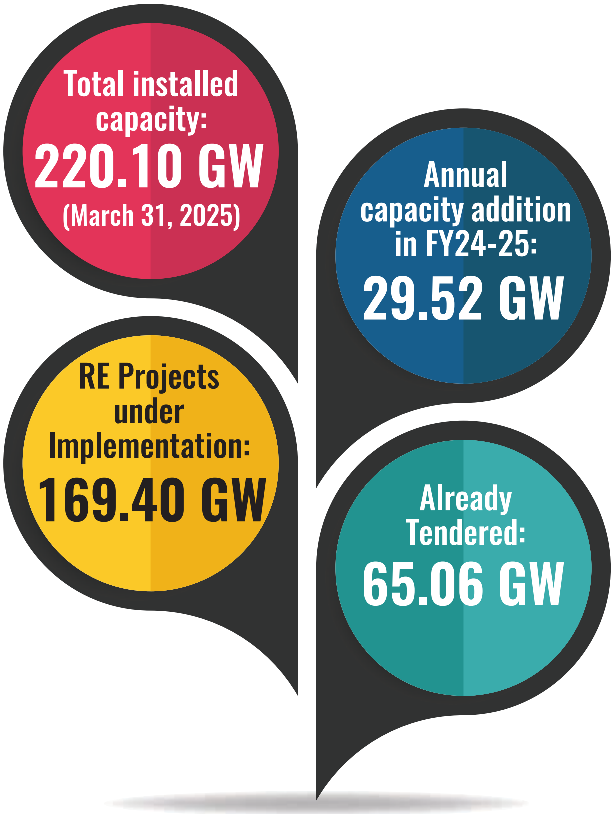
India's total installed RE capacity reaches 220.10 GW with a record addition of 30 GW

Solar energy a major contributor to capacity expansion with 23.83 GW added in FY2024-25, with wind energy adding new capacity of 4.15 GW.

The Ministry of New and Renewable Energy (MNRE) has reported robust progress in India's clean energy sector for FY2024-25, as per a report by PIB. With a record annual capacity addition of 29.52 GW, the total installed renewable energy (RE) capacity in the country has reached 220.10 GW as on March 31, 2025, up from 198.75 GW in the previous fiscal. This performance reflects India's steady advancement towards the target of achieving 500 GW of non-fossil fuel-based capacity by 2030.

Solar Energy Drives Growth

Solar energy contributed the most to the year's capacity expansion, with 23.83 GW added in FY2024-25, a significant increase over the 15.03 GW added in the previous year. The total installed solar capacity now stands at 105.65 GW. This includes 81.01 GW from ground-mounted installations, 17.02 GW from rooftop solar, 2.87 GW from solar components of hybrid projects, and 4.74 GW from off-grid systems.



Steady Rise in Wind Installations

Wind energy also witnessed sustained progress during the year, with 4.15 GW of new capacity added, compared to 3.25 GW in FY 2023-24. The total cumulative installed wind capacity now stands at 50.04 GW, reinforcing wind energy's role in India's renewable energy mix.

Bioenergy and Small Hydro Power Maintain Momentum

Bioenergy installations reached a total capacity of 11.58 GW, including 0.53 GW from off-grid and waste-to-energy projects. Small hydro power projects have achieved a capacity of 5.10 GW, with a further 0.44 GW under implementation. These sectors continue to complement the solar and wind segments by contributing to the decentralised and diversified nature of India's energy landscape.

Expanding Pipeline of Clean Energy Projects

In addition to the installed capacities, India has 169.40 GW of RE projects under implementation and 65.06 GW already tendered. This includes 65.29 GW from emerging solutions such as hybrid systems, round-the-clock (RTC) power, peaking power, and thermal + RE bundling projects. These initiatives represent a strategic shift towards ensuring grid stability and reliable supply from renewable sources.

MNRE, under Union Minister of New and Renewable Energy Shri Pralhad Joshi, has been taking various key initiatives to achieve the vision of 500 GW of RE by 2030. The continued growth reflects India's commitment to its climate goals and energy security.

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- Amit Gupta, Chairman, RBSM 2025

As Chairman of RBSM at ELECRAMA 2025, **Amit Gupta** shares how it served as an important business platform globally and more...

Fostering international trade and facilitating networking: RBSM at ELECRAMA 2025 has been undoubtedly the biggest meeting place for international buyers looking to source electrical products and equipment from India. It was a privilege to welcome about 400 international delegates from around 65 countries. This event was a truly global platform for exchange of ideas, learning from best practices and competitive technological solutions. RBSM had a significant impact by fostering international trade and investment and facilitating networking and collaboration. It served as a catalyst, enabling Indian companies to tap into new markets and build relationships with international partners. With RBSM, global buyers saw India as a trusted global partner and friend for international business.

Promoting exports and the 'Make in India' initiative: Over the years, India's export potential is getting bigger, better and bolder. Some Indian manufacturers are sitting on world-class quality products to serve global markets. Indian products are competitive on the world stage. There is a huge demand for electrical products due to infrastructure growth as well as the acceleration of energy transition happening in developed markets. Platforms like ELECRAMA helped bring global buyers through the RBSM route. This helped promote government initiatives like 'Make in India' and enabled Indian businesses to showcase their manufacturing prowess to global buyers, thus promoting exports and also helping them expand their global footprints.

Sections and categories with higher traction: RBSM buyers showed keen interest in smart grid solutions, energy storage systems, EV charging and renewable energy technologies. Some of the product categories that saw greater traction were power cables, wires, conductors, switchgears and control panels, transmission line towers, insulators, transformers and smart metres, among others.

Value of business enquiries at RBSM 2025: This edition of RBSM 2025 witnessed more than 3,000 meetings in three days with business interest from global buyers from 65 countries of circa US$ 4 billion. MoUs were also signed with TEMCA – Thailand, EURELECTRIC – Belgium, APREL – Romania, and TEEAM – Malaysia, which will enable stronger ties and facilitate trade and investments between businesses within these countries.

"DBSM truly helped bridge the gap between what businesses offer and what utilities need."

- Hartek Singh, Chairman, DBSM

As Chairman of DBSM at ELECRAMA 2025, **Hartek Singh** shares how the platform leveraged as an interactive opportunity between companies and utilities, and more...

Important business platform: DBSM was a great platform for Indian MSMEs to directly connect with key decision-makers from public and private utilities. It created real business opportunities by encouraging focused, one-on-one conversations that often turned into actionable leads. It truly helped bridge the gap between what businesses offer and what utilities need.

Interactive opportunity: The setup allowed for meaningful, two-way discussions. Companies could showcase their solutions while also learning about upcoming utility requirements. With a good mix of government and private players, plus shared logistics, it was easy to network and have open, informal conversations that often led to deeper engagement.

Attractive business enquiries: Apart from the above, interest was around smart and sustainable solutions – smart metres, automation, energy-efficient gear, EV infrastructure, and digital controls saw the most traction. Utilities were clearly looking for scalable, future-ready technologies to support their modernisation and green energy goals.

the Make in India initiative of the Government of India. The Domestic Buyer-Seller Meet (DBSM) is a platform that strengthens Indian businesses, especially micro, small and medium enterprises (MSMEs), opening the world market for them to achieve more business in public and private utilities.

RBSM

For the first time, an International Evening 'Bharat – The Vishwa Mitra' was organised at ELECRAMA 2025, providing a wider experience on India's culture and a unique platform to network. Chief Guest Shri Piyush Goyal, Hon'ble Union Minister of Commerce and Industry, and H.E. Dr. Philipp Ackermann, Ambassador, Embassy of Germany, India, addressed the special plenary sessions at the event.

Notably, about 1,312 applications were received from the integrated registration portal for RBSM. With more than 1,911 meetings held, business enquiries reported were worth US$ 3.78 billion. RBSM witnessed 442 approved buyers. Interestingly, 387 buyers from 62 countries arrived to do business at this significant platform. These included buyers from countries such as Australia, Azerbaijan, Bahrain, Belgium, Benin, Bhutan, Brazil, Cambodia, Cameroon, Chile, Congo, Côte d'Ivoire, Egypt, Ethiopia, Finland, Ghana, Guinea, Indonesia, Jamaica, Jordan, Kazakhstan, Kenya, Kuwait, Laos, Lebanon, Lesotho, Madagascar, Malawi, Malaysia, Malta, Mauritius, Myanmar, Namibia, Nepal, Nigeria, Oman, Philippines, Qatar, Russia, Rwanda, Saudi Arabia, Somalia, South Africa, South Korea, South Sudan, Sri Lanka, Sudan, Swaziland, Tajikistan, Tanzania, Thailand, Togo, Tunisia, Turkey, Uganda,

the UAE, the UK, Uruguay, Vietnam, Yemen, Zambia, and Zimbabwe.

RBSM 2025 witnessed buyers from 10 new countries this edition – Cameroon, Côte d'Ivoire, Jamaica and Madagascar from Africa; Brazil, Uruguay and Chile from LAC; South Korea from North East Asia; and Belgium and the UK from Europe.

The Energy Minister of Guinea, high level delegation from Oman, and delegation from Russia also visited the mega event.

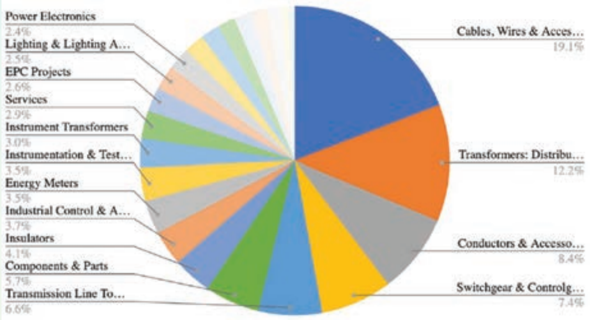
The following MoUs were also signed at RBSM 2025:

- Romania – Romanian Ownership Association for Electrotechnique Industries (APREL)
- Thailand – Thai Electrical & Mechanical Contractors Association (TEMCA)
- Malaysia – The Electrical and Electronics Association of Malaysia (TEEAM)
- Belgium – The Union of the Electricity Industry (Eurelectric).

The high-quality buyer profile largely comprised top-level and senior management from utilities and equipment buyers. About 86 were buyers from government or utilities, 29 from EPC companies, and 327 were electrical equipment buyers.

Here's a graph showcasing products that buyers were most interested in.

PRODUCTS OF INTEREST AT RBSM



DBSM

Business worth US$ 2.26 billion was generated under the DBSM platform at ELECRAMA 2025 with more than 7,528 meetings. Participants comprised a mix of government and private utility and non-utility organisations. With 278 utility officials from government and private utilities nominated, the non-utility officials nominated were 93. Organisations other than state utilities wherein nominations were received included renewable companies such as Hero Future Energies, ONIX Renewables, HARTEK Group, ReNew Power, EDF Renewables, EDEN Renewables, Essar Renewables and AMPIN Energy Transition, among others; EPC companies such as Larsen & Toubro Limited, L & T Sufin, Techno Electric & Engineering Co Ltd, Shyama Power India Limited and JSW Group; PSUs such as Engineers India, ONGC Tripura, Numaligarh Refinery, Oil India Duliajan, Indian Oil Corporation Delhi, IOCL Haldia Refinery, Oil India Delhi and IOCL Mathura Refinery, among others; and private utilities such as The TATA Power Company Limited, TATA Power Central Odisha Distribution and BSES Rajdhani Power Limited.

Platforms such as these are testament to India's growth story, proving to be a one-stop destination for forging new business ties and growth opportunities.

India's Expanding Free Trade Agreements' Landscape

In times marked by escalating global trade tensions, geopolitical uncertainty, IEEMA Research Team presents a lowdown on the winning prospects of India's strategic free trade agreements vista.

In recent years, the landscape of trade agreements has evolved significantly, reflecting broader economic, geopolitical, and technological changes. The direction of global trade agreements is increasingly being shaped by the need for resilience, sustainability, and digital transformation.

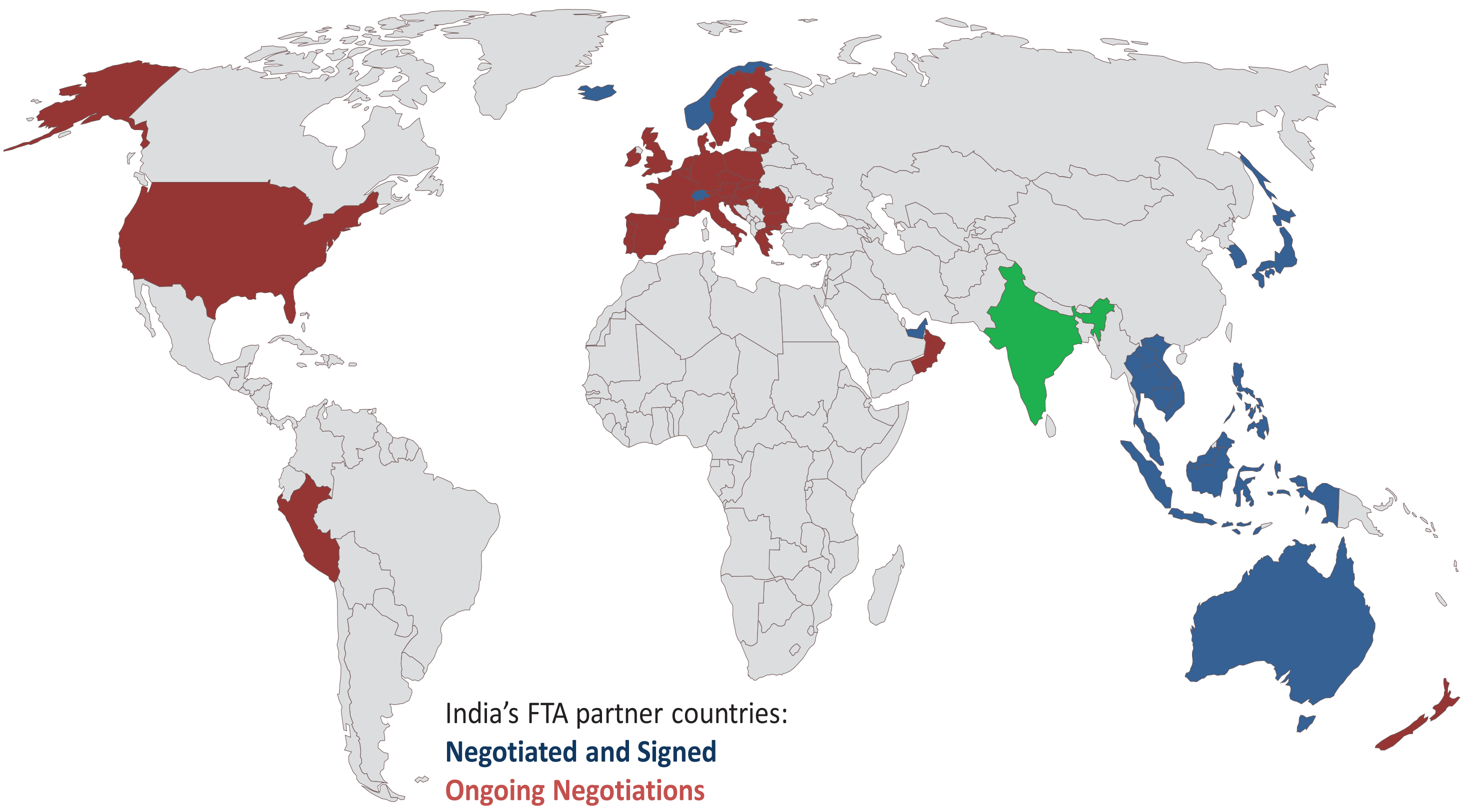
In brief, trade agreements are formal accords between countries aimed at facilitating smoother and mutually beneficial economic exchange. These agreements help reduce or eliminate trade barriers such as tariffs, quotas, and import duties, thereby promoting international trade, investment, and economic integration. Depending on their scope and depth, trade agreements can range from basic tariff reductions to comprehensive arrangements covering a wide range of areas.

Trade Agreements are various types, such as

Free Trade Agreement (FTA): An FTA is an agreement to lower or eliminate tariffs, import quotas, and preferences on most (if not all) goods and services exchanged between nations.

Comprehensive Economic Partnership Agreement (CEPA): A CEPA extends beyond an FTA and covers trade in goods and services, investments, and cooperation in areas like customs procedures, standards, and intellectual property. It normally covers non-tariff barriers, regulatory matters, and it seeks deeper economic integration.

Comprehensive Economic Cooperation Agreement (CECA): Like CEPA, a CECA is a more comprehensive agreement involving trade in goods, services, investment, and frequently, economic



India's Free Trade Agreement Landscape: Status and Trade Data

Country/ Bloc	Year	Status	India's export (USD million)		India's import (USD million)	
			2022-23	2023-24	2022-23	2023-24
Negotiated and signed						
Singapore CECA	2005	Active	191.08	224.33	840.81	920.50
ASEAN FTA	2009	8 rounds of review completed; slow pace of review	752.16	833.47	1529.60	1722.36
South Korea CEPA	2009	Active	79.87	88.05	949.90	975.00
Japan CEPA	2011	Active	182.72	188.42	804.19	816.64
Malaysia CECA	2011	Active	91.41	117.96	151.83	134.11
UAE CEPA	2022	Active	552.59	701.04	69.25	141.42
Australia CECPA	2022	Active	369.14	356.33	15.75	15.72
EFTA TEPA	March 2024	Signed. In March 2025, the Switzerland Parliament approves an FTA with India. Iceland, Liechtenstein, and Norway have yet to be ratified. Includes investment commitments.	32.76	28.74	124.59	133.52
Ongoing Negotiations						
Oman CEPA	Started in November 2023	Aim to finalise by the end of 2025.	121.00	93.67	1.59	1.88
Peru FTA	Pause (June 2024)	8 rounds completed; pending resolution of key issues.	53.89	23.43	0.06	0.05
European Union FTA	Ongoing (Restarted 2022)	10 rounds completed	2536.75	2724.78	2589.84	2592.69
UK FTA	Ongoing (Started 2022)	13 rounds completed; advanced stage, but pending resolution of key issues.	457.76	631.13	254.59	283.99
Negotiations to be started						
New Zealand FTA	Announced March 2025	To be signed in 60 days;	13.17	12.14	3.37	3.06
USA BTA	Announced February 2025	Committed to be negotiated by fall 2025.	2912.08	2894.93	757.58	787.75

Data Source: Ministry of Commerce and Industry
Note: Data is a total of 276 IEEMA HSN Code (8-digit level)

cooperation in various sectors. CECA and CEPA are frequently used synonymously, but CECA may emphasise more on cooperation and capacity-building activities along with trade liberalisation.

Bilateral Trade Agreement (BTA): A BTA is a straightforward agreement between two nations to reduce or eliminate trade barriers on specific goods or sectors. It is typically less detailed than a FTA, CEPA, or CECA, and focuses on selective trade advantages.

These trade agreements tend to include a broad scope of issues, such as tariff and non-tariff barrier removal, trade in goods and services, investment flows, customs cooperation and trade facilitation, standards, technical regulations, and sanitary measures (SPS/TBT), intellectual property rights (IPR), government procurement, etc.

India's Expanding FTA Landscape

India's trade strategy has undergone a significant transformation, moving from a traditionally protectionist approach to one focused on deeper global economic engagement. Over the last two decades, the country has entered into several FTAs aimed at expanding market access, improving competitiveness, and embedding the Indian industry more firmly within global value chains. This shift holds particular importance for the electrical and electronics sector, where supply chains, standards, and technology flows are increasingly global in nature.

FTAs play a crucial role in enhancing market access, cost efficiency, and overall competitiveness through tariff reductions, standard harmonisation, and supply chain integration. These agreements are instrumental in advancing India's goal of becoming a global hub for manufacturing and exports, especially in fast-growing sectors like electrical and electronic equipment.

Navigating Opportunities and Challenges for the Electrical Sector in the FTAs

Opportunities

These agreements have unlocked significant opportunities for the electrical sector by facilitating tariff reduction, enhancing market access, and fostering regional integration.

For instance, under India's existing FTAs, the reduction of import duties on key electrical components and machinery has **supported increased exports.** The FTAs with UAE and Australia have opened access to high-growth opportunities further boosting competitiveness by eliminating tariffs on over 90% of Indian goods, including electrical equipment, enabling faster penetration into the Middle East and North Africa (MENA) regions. Australia's Economic Cooperation and Trade Agreement (AI-ECTA) has enhanced market entry for Indian products.

These agreements have not only strengthened India's presence in global markets but also improved the **sector's competitiveness** by encouraging the adoption of global standards and advanced manufacturing practices. The FTAs have made India a more attractive destination for foreign investment, particularly in joint ventures and technology collaborations in areas like energy, smart grid.

FTAs with the European Free Trade Association (EFTA) including countries like Iceland, Liechtenstein, Norway, and Switzerland, has a clause of US$ 100 billion of investment that can be seen as an opportunity for technology transfer and innovation through collaborative R&D and technical training initiatives under this agreement.

Moreover, **the diversification of supply chains**—supported by trade with countries like Australia, UAE, and ASEAN—has reduced dependence on a few geographies, improving resilience. The recently signed FTA with the European Free Trade Association (EFTA), that includes Iceland, Liechtenstein, Norway, and Switzerland, has a clause noting **investment of US$ 100 billion** that can be seen as an opportunity for technology transfer and innovation through collaborative R&D and technical training initiatives.

Looking ahead, the signing of FTAs with Peru, Oman, the European Union, the USA, and New Zealand can further broaden the horizon. These agreements hold the potential for greater market access in Latin America, strategic entry into the EU and US high-end markets, and access to advanced technologies and certifications that will elevate the global competitiveness of Indian electrical manufacturers.

Challenges

While India's FTAs have opened new avenues for growth, Indian sectors have not been able to leverage FTAs as an opportunity to reach their full potential.

One of the primary concerns **is market access issues.** In many FTAs, while India has received immediate tariff reductions leading to secure easier access for Indian companies, the products struggle to meet stringent technical and regulatory standards abroad. This has created an uneven playing field, especially in agreements with advanced economies like Japan and South Korea, where Indian manufacturers face high non-tariff measures (NTMs) such as complex certification processes, product testing requirements, and compliance with international standards.

Another major challenge in the limited utilisation of FTAs is a **lack of awareness among manufacturers** about navigating FTA rules of origin, documentation processes, and compliance requirements. This limits their ability to access preferential tariffs and market benefits. In some cases, preferential market access remains underutilized due to **inadequate alignment to international quality standards** with those of partner countries, including Japan, South Korea, and also EFTA.

Concerns also arise regarding the surge in imports, particularly under the ASEAN FTA, which has already resulted in increased imports of electrical components and finished goods, often at the expense of domestic manufacturers.

Additionally, the **absence of mutual recognition agreements** in testing, inspection, and certification has led to duplication of efforts and increased costs for Indian exporters. Supply chain issues also persist, as several FTAs have not fully addressed logistics bottlenecks or facilitated seamless integration with regional value chains, limiting the competitiveness of Indian products in markets like ASEAN and the Middle East.

The FTAs have made India a more attractive destination for foreign investment, particularly in joint ventures and technology collaborations in areas like energy, smart grid.

IEEMA, the apex association representing manufacturers of electrical, industrial electronics, and related equipment in India, is actively engaging with relevant stakeholders to provide input during the negotiations of these major FTAs. IEEMA has submitted feedback for the India–New Zealand and India–USA Product Specific Rules (PSRs), where we are adhering to twin criteria: Change in Tariff Sub-Heading plus Value Addition of 40% (CTSH + 40%).

Impact of Global FTAs on India's Electrical Sector

Globally, countries are aggressively pursuing FTAs to secure market access, each striving to gain an advantage over the others. The global trading environment is becoming increasingly competitive and strategic. This evolving FTA scenario poses both opportunities and challenges for Indian companies.

1. **Increase in Competition in Export Markets**
   Globally, countries are proactively signing FTAs to increase market access. The primary example is the UAE. In the last five years, the UAE has signed over 20 FTAs, including with countries like Indonesia, Vietnam, Turkiye, etc. Due to this, the electrical sector may see immense competition in the country and the Middle East region.

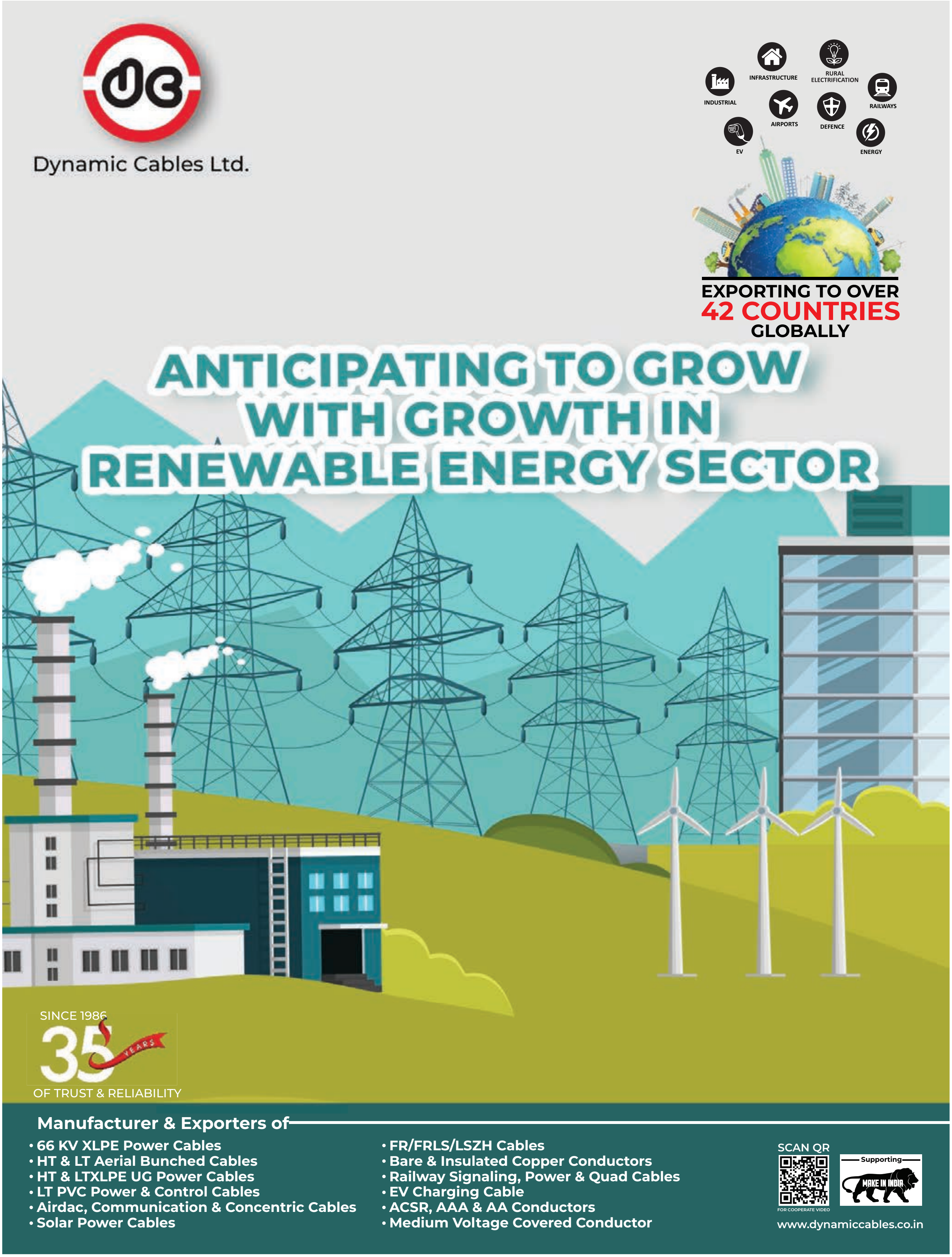
Absence of mutually recognised agreements in standards of testing, inspection, and certification has led to duplication of efforts and increased costs for Indian exporters.

2. **Access to Raw Materials and Critical Inputs**
   Many electrical products depend on imported raw materials and critical intermediates like CRGO steel, semiconductors, and power electronics. FTAs between other countries may enable easier and cheaper access to such materials, giving their industries a cost advantage over Indian manufacturers who face higher input costs due to import duties or limited sourcing options.
3. **Standards and Regulatory Alignment**
   Modern FTAs are progressively dealing with non-tariff matters like standards, testing, certification, and sustainability. This calls for Indian products to proactively upgrade standards, particularly regarding green energy equipment or smart metering; Indian product quality will make roads in high-value international markets. This necessitates strategic Indian standard alignment with the world's best practices and industry participation.

Recommended Policy Actions

As India is also signing FTAs to enhance competitiveness and leverage global market opportunities, the following recommendations are aimed at strengthening India's position in global trade while safeguarding and promoting the domestic electrical manufacturing ecosystem.

1. <u>Review and Rationalise:</u> Ongoing exercise to review FTAs, like with ASEAN, to address asymmetries.
2. <u>Push for Investment and Technology Collaboration:</u> Especially in FTAs with developed economies like UK, EU.
3. <u>Enhance Export Readiness:</u> Help MSMEs understand and utilise FTAs better through trade facilitation.
4. <u>Strengthen Domestic Standards:</u> Align with global standards to prevent rejection of exports.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CEA launches STELLAR, a useful tool for discoms and load despatchers

The indigenously developed tool is specifically designed to assist states in carrying out a comprehensive resource adequacy plan, in line with the resource adequacy guidelines issued by the Ministry of Power in June 2023.

The Central Electricity Authority (CEA) has launched State of art totally Indigenously developed Resource adequacy model (STELLAR) on April 11, 2025. An indigenously developed integrated generation, transmission and storage expansion planning model with demand response, it is a vital resource adequacy tool. It was launched by Shri Ghanshyam Prasad, Chairperson, CEA, in the presence of Shri Alok Kumar, Ex-Secretary (Power) and partner The Lantau Group (TLG), among representatives from state power utilities. This software model is planned to be distributed to all states and discoms free of cost, as per a report on PIB.

The indigenously developed tool is specifically designed to assist states in carrying out a comprehensive resource adequacy plan, in line with the resource adequacy guidelines issued by the Ministry of Power in June 2023.

After the issuance of Resource Adequacy Guidelines, CEA has been carrying out the Resource Adequacy (RA) plans for all discoms. To begin with, CEA completed the exercise for all discoms up to 2032, with all of them having been updated to 2034-35 now. CEA has also finished the national level exercise up to 2034-35.

Since the plan is dynamic and is mandated to be revised every year, the idea was to develop a common tool for all and share it free of cost, mentions the PIB report. It will also help integrate studies easily and bring out optimum solutions for the country.

The model explicitly considers:

- Chronological operation of the power system.
- All unit commitment constraints, including technical minimum, minimum up and down times, and ramp-up/ramp-down rates.
- Endogenous demand response.
- Ancillary services, and many more.

The software has been developed entirely in India with the active guidance of CEA, ensuring complete transparency. CEA will update and upgrade this tool basis further suggestions from users (discoms and load despatchers) of this software.

The launch event highlighted the collaboration between CEA, TLG and the Asian Development Bank (ADB) under the Technical Assistance programme.

Benefits of STELLAR

- Ensuring adequate resource adequacy (neither less nor more) in the electricity grid. Zero load shedding, no stressed capacity and least cost solutions.
- Cost optimisation of power system generation expansion and system operations while considering the benefit of demand response.
- Optimisation of energy and ancillary services.
- Optimisation of size and location of storage.

Challenges Faced in Integrating Inverter Based Resources

This paper by **SV Varadarajan, Retired Technical Director, M. N. Dastur & Company (P) Ltd, Chennai,** analyses the difficulties encountered while integrating inverter-based resources in the grids, while discussing a number of solutions to build resilient hybrid grids that are under research, trial, and implementation.

The increase in the population of renewable energy (RE) sources has caused a disruption in the operation of conventional electrical power grids. Photovoltaic (PV) and wind energy sources have zero inertia as no rotating machines are involved. Instead, their front ends comprise inverters. This has caused challenges to the operations of conventional grids that have been designed hitherto based on inertia and response characteristics of synchronous generators. This paper analyses the difficulties encountered while integrating inverter-based resources in the grids. A number of solutions to build resilient hybrid grids are discussed, which are under research, trial, and implementation.

1. Introduction

The stability of large electric power grids up to present times has been determined by the inertia and response time of synchronous generators that are synchronised and supplying power to them. Prime movers for these generators are either steam or water or gas turbines. Today's electric power grid is rapidly changing. An increasing proportion of generation from non-traditional sources such as wind and solar (among others) as well as energy storage devices such as batteries are being connected to the electricity grid on a continuous or intermittent basis. These renewable power generation sources are also called distributed energy resources (DER) as they are located near to consumers (residential, group of residences [micro-grid], commercial or industrial) and connected to the grid at various locations, mostly at the distribution voltage level, except in the case of mega-sized plants. Thus, the 'conventional grid' fed by only synchronous power generators is slowly changing into a 'hybrid grid', which is a combination of traditional generators and DER. The most crucial part is that all these renewable sources, including battery storage systems whose outputs are in direct current (DC), are connected to the alternating current (AC) power system, either at the local level or at the grid level, through the application of power inverters, associated electronics, and software. Hence, these sources are called inverter-based resources (IBR). In this paper, challenges faced in the integration of IBR into the grid are briefly discussed, together with applicable solutions.

2. Typical Operation of IBR

In a representative IBR, the energy produced is consumed locally at the source itself. This is due to improvement in technology, which is progressively reducing the cost of generation through these sources. However, wind and solar sources are highly dependent on the weather and their output is not constant. Their sizes are also assorted. There are small residential rooftop systems. There are also large-scale plants meant for direct evacuation to the grid at high voltage. Moreover, the rooftop residential systems are interconnected to local distribution systems called microgrid, while the power from mega plants are evacuated to the grid directly through high voltage transmission lines.

3. Size of Short Circuit Current

When an interconnection from a generating source takes place at a local bus, the available short circuit current from the grid side is reduced, while any interconnection at the grid level provides higher short circuit current.

4. Integration of RE in the Grid

There are two main types of RE generation resources: Distributed generation, which refers to small-scale renewable generating plants on the distribution grid and consumed by the local loads then and there; and, centralised, utility-scale generation, which refers to larger projects that connect to the grid through transmission lines[1].

(a) Utility-scale generation:

Centralised, utility-scale RE plants are comparable to fossil-fueled power plants and can generate hundreds of megawatts (MW) of power. Like natural gas, coal and nuclear plants, large renewable plants produce power that is sent across transmission lines, transformed to lower voltage, and transmitted across distribution lines to homes and commercial buildings.

However, unlike conventional fossil-fuel plants, RE plants are typically not dispatchable (or able to generate power whenever called upon), as they depend on variable resources like the sun and wind, whose intensity changes over the course of a day. However, when RE is available, sources from wind and solar are prioritised in the dispatch order. Wind and solar have zero fuel costs, so their production is used before other generator types because they are the cheapest energy source available[1]

(b) Distributed generation

Small residential and commercial renewables (range between 5 and 500 kilowatts) are extensively installed at residences and at small factories. Often, these are subsidised by governments. Most of these small-scale renewables are solar panels, which are easily customisable in size. These distributed resources, such as roof-top solar panels, are typically located on-site at homes or businesses. Unlike large, centralised renewable plants that connect to the grid through high-voltage transmission lines, distributed resources of small capacity are connected to the grid through electrical lines in the lower voltage distribution network, which are the same lines that deliver electricity to customers[1].

In most instances, these small installations are classified as 'behind the metre', which means that the electricity is generated for on-site use (such as a rooftop solar system that supplies a household with power). These small, distributed projects typically lower the demand for electricity at the source rather than increasing the supply of power on the grid. For example, when the sun is shining, a house that has solar panels on its roof may not need electricity from the grid because its solar panels are generating enough electricity to meet the residents' needs.

The capacity of community scale renewables is between rooftop projects and utility-scale capacities. These are also connected to the grid through distribution lines, and are hence, also considered to be distributed generation. However, unlike small rooftop renewables, community-scale renewables are wired 'in front of the metre', meaning that the power they generate is used partially on-site and the balance flows onto the distribution grid to be used by other homes and businesses locally[1].

5. Comparing the Two Generation Types

Both centralised and distributed-generation renewables have both, merits and demerits for customers and grid operators. From an economic perspective, centralised utility-scale renewables are much cheaper than distributed resources due to economies of scale.

In addition to being cheaper, centralised projects are often much easier for the grid operator to control. Because distributed renewables are often small and behind the metre, they can be difficult to track from a grid operator's perspective and can significantly complicate load forecasting. Grid operators usually only know that distributed renewables exist when they reduce customer demand for electricity significantly during certain periods.

However, distributed renewables can provide the grid with benefits that large projects cannot. Since the energy from distributed generation is typically used on-site or nearby, distributed energy resources can significantly reduce energy losses that occur when electricity is carried on transmission lines, and they can avoid the cost of new transmission and distribution infrastructure. If they are connected to micro grids, distributed renewables can also provide greater resilience during storms that disrupt the power grid by providing power locally even when a larger grid experiences outages[1].

6. Challenges in a Hybrid Grid

When a grid becomes hybrid, that is a combination of both traditional turbo generators and IBR, it becomes complex as the basic characteristics, namely, the inertia and response times of turbo generators are different from those of the IBR. Adding to this complexity is the fact that the IBR could be many with their quantities increasing on a daily basis and which are well spread out and which could be connected throughout the grid at several points. In comparison, turbo generators that are large in capacity are comparatively few in number and are located (like in pitheads or at load centres) and connected at known (geographical) points in the grid. Operating hybrid power systems with significant amounts of inverter-based resources poses a challenge due to lack of previous experience. Recognised formal standards and/or guidelines are also currently not available, although a lot of research work is going on in this field.

7. Introduction to the Two Methods of Controlling Inverters in IBR:

The two broad types:

As of current research and implementation, inverter controlling methods can be broadly classified as (i) grid forming controls (GFM) – which use voltage control and (ii) grid following controls (GFL) – which apply current control. GFM is the latest initiative considered as a potential solution for future grid operations, while GFL has been in existence ever since the first IBR was integrated to the grid.

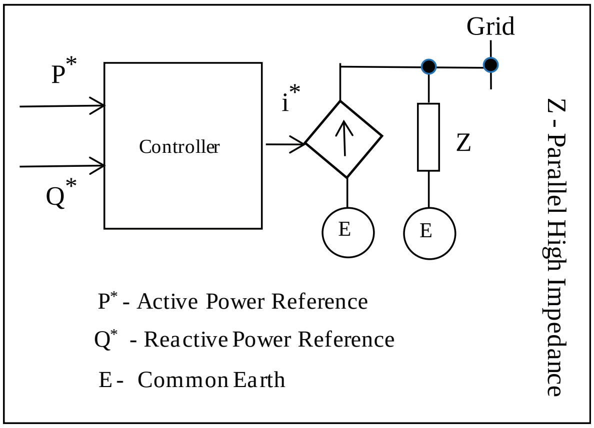
General features:

Both types of inverters possess fast response capabilities. GFL inverters have current source characteristics. All the IBR extensively use GFL inverters. They attempt to maintain active or reactive power constant in a transient time frame. In contrast, GFM inverters behave as voltage sources and have been in successful application in microgrids as of now. Research is currently ongoing in implementing GFM inverters in large grid systems. These inverters maintain their internal voltage constant and are capable of supplying active or reactive power rapidly when the grid voltage changes due to disturbances[2].

Basic scheme of a GFL inverter:

GFL inverters act as a controlled current source, and it follows a reference of Voltage Angle. It can be interpreted as an ideal current source[3] in parallel with a high impedance (Z) as shown in Figure 1.

Figure-1: Typical CSI Block Diagram:



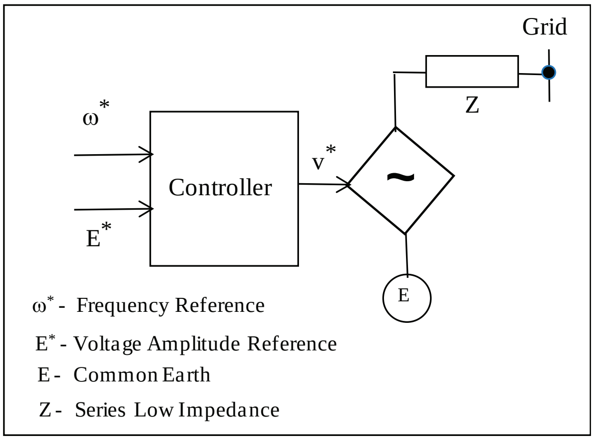
Credit: https://www.psmaconsulting.com/

GFL inverters inject active and reactive power to the grid according to the reference current or power set point. The inverter control is synchronised with the grid voltage through a phase-locked loop (PLL) controller, discussed later in this paper. PLL tracks the angle of the grid voltage (θ), which will be used for synchronisation. The phase-locked loop does not generate its own reference and it always needs a reference (voltage angle) to follow[3].

Basic scheme of a GFM inverter:

These inverters are basically controlled voltage source[3] (voltage source inverters or VSI) and they perform in the grid similar to traditional synchronous generators in what is called virtual synchronous machine (VSM) mode. This is discussed later in this paper with suitable block diagram. GFM and GFL inverters have different synchronisation techniques. In GFM inverter control, the synchronisation is based on the active power transfer and the 'swing equation'. The GFM inverter is considered as an ideal voltage source *in series with a low impedance* (Z), which is similar to the synchronous generator concept. Figure 2 shows a typical block diagram for GFM inverter control.

Figure-2: Typical VSI Block Diagram



Credit: https://www.psmaconsulting.com/

The swing equation:

The 'swing equation' in a power system is a nonlinear differential equation that describes the dynamic behaviour of a synchronous generator's rotor angle (δ), relating the angular acceleration of the rotor to the difference between the mechanical power input (P_m) and electrical power output (P_e) during transient conditions. It shows the amount of rotor swing in response to power imbalance caused by a disturbance. In one of the variations (like in VSM), GFM inverters are modeled as per the swing equation, which is described in a later section.

Derivation[4]:

Let us assume a generator is supplying active power P and reactive power Q.

Let P_m be the mechanical power input to the generator.

Let T_m be the mechanical torque input to the generator.

Let T_a be the accelerating torque.

Let T_e be the electromagnetic torque developed by the generator.

Let J be the moment of inertia of the rotor.

Let w be the angular speed.

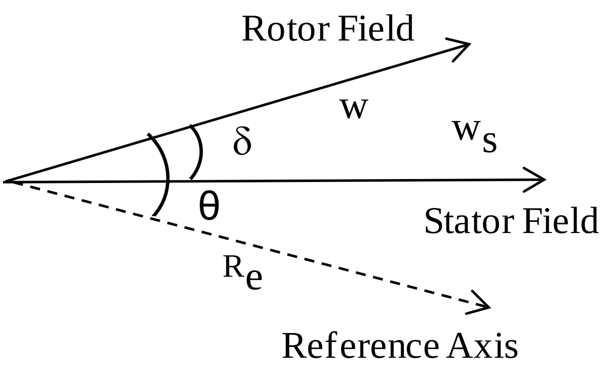
The torque equation of the rotor can be stated as:

$T_m - T_e = T_a = J*(dw/dt)$

Let θ be the angular position of the rotor at a given time, t.

As the value of θ changes over time, it is referenced to an axis as shown below:

The following figure depicts the angular position of the rotor field with respect to stator field and reference axis:



From the above figure:

$\theta = w_s * t + \delta$ Equation-1

Where:

θ – Angle between rotor field and reference axis in Radians

w_s – Synchronous speed, in RPM

δ – Angular displacement, in Radians
Double differentiating Equation - 1, we get Equation-2 stated below:

$$\frac{d^2\theta}{d^2t} = \frac{d^2\delta}{d^2t}$$

Angular acceleration of the rotor,'α', is given by Equation-3, stated below:

$$\alpha = \frac{d^2\theta}{d^2t} = \frac{d^2\delta}{d^2t}$$

Accelerating torque, T_a, in a synchronous generator is equal to the torque at the shaft, T_m less the electromagnetic output torque, T_e, ignoring the damping effects. (All torque values are in units of N.m)
$T_a = T_m - T_e$ ... Equation-4.
Angular momentum of the rotor M = J* w ... Equation-5
Where:
w – Angular speed of the rotor, RPM
J – Moment of inertia of the rotor, $kg.m^2$
M – Angular momentum of the rotor, $kg.m.^2s^{-1}$
Multiplying both the sides of Equation-4, by 'w', we get:
$w*T_a = w*T_m - w*T_e$, which can be rewritten in terms of power as, $P_a = P_m - P_e$
Where,
P_a – Accelerating power: P_m – Mechanical power input: P_e – Electrical power output.
Multiplying both sides of Equation-2 by the rotor moment of inertia, 'J', we obtain Equation-7:
$J*[d^2\theta / d^2t] = T_a = J*[d^2\delta / d^2t]$
(as torque = Moment of inertia multiplied by angular acceleration)
Multiplying both sides of above Equation-7, by 'w', we obtain:

$$w*J*\frac{d^2\delta}{d^2t} = w*T_a ......Equation\text{-}8$$

Equation-8 can be rewritten as: (substituting M for [w*J] and P_a for [w*T_a])

$$M*\frac{d^2\delta}{d^2t} = P_a = P_m - P_e ....Equation\text{-}9$$

Equation-9 is called 'swing equation', showing the relationship between angular acceleration ($d^2\delta/d^2t$) and accelerating power (P_a).

Applications of 'swing equation' are briefly given below:
(a) Transient stability analysis: By solving the swing equation numerically, one can simulate the system's response to a disturbance and determine, if the rotor angle remains within stable limits.
(b) Critical clearing time: This analysis helps identify the maximum duration a fault can be withstood before the system becomes unstable.
(c) Control system design: Understanding the 'swing equation' is critical for designing control functions to increase power system stability.

Synchronous generators vs. inverter controls:
Synchronous generators change their power output to regulate their terminal voltages and respond to a change in grid frequency. It is well known that the generator excitation controls the output voltage and the turbine governor controls the frequency of generation. These types of primary, secondary, and tertiary controls and voltage controls are called 'grid-forming'. In contrast, most of the inverter-based generation sources generally use phase-locked loops (PLL), which rely on the grid voltage, which is set by synchronous generators operating in conventional power plants. These types of inverter-based generation controls are referred to as grid following. In case of faults and outages of the power grid, islanded systems comprising only inverter-based resources will not be capable of functioning independently. Similarly, after a blackout, grid following inverters cannot support the restoration process of the bulk power system (due to lack of grid voltage reference) unless conventional generators with black-start capability are available in the grid[5]. A few inverters may disconnect and/or cease operations as a result of transmission faults and this behaviour is contrary to the desired behaviour of resources connected to the bulk power system during a severe event. The performance of phase-locked loop (PLL) controlled inverters on the distribution system is a major topic of discussion and has resulted in updated equipment standards[6].

Salient features of grid-coupled inverter controls:
(i) Source side (DC) control: Manages the DC link voltage from the renewable source (like solar panels) using maximum power point tracking (MPPT) algorithms to extract maximum power.
(ii) Grid (AC) side control: Controls the AC output of the inverter to ensure synchronisation with the grid, including active and reactive power regulation, voltage and frequency control, and harmonic filtering.

8. Brief Discussion on Power System Stability

Power system stability of a grid in general means the ability of the system to remain in a state of equilibrium during normal operating conditions and its capacity to regain an acceptable state of equilibrium after an occurrence of a disturbance such as a fault in the transmission lines or, sudden loss (disconnection due to line tripping) of a major consumer (load) or sudden loss of generation (loss of a generator due to its own fault)[7]. The power system stability may be further divided into (a) angle stability (b) voltage stability and (c) frequency stability according to the main system variables.
(a) Rotor angle stability:
Rotor angle stability refers to the ability of synchronous machines connected to a grid

to remain in synchronisation even after being subjected to a disturbance[8]. It is the ability to maintain and/or restore equilibrium between electromagnetic torque and mechanical torque of each synchronous machine in the system. Instability results in increasing angular swings of some generators, leading to their loss of synchronisation with other generators.

(b) Voltage stability:

(i) Overview

Voltage stability refers to the ability of a power system to maintain steady voltages in the grid even after the occurrence of a disturbance. It ensures that the voltage throughout the system stays within a specified range under both normal and disturbed conditions. It calls for capacity to maintain and or restore equilibrium between load demand and power supply in the grid[7,8].

Instability means progressive fall or rise of voltages in all or in the affected buses in the same grid. Voltage instability results in either loss of load or tripping of transmission lines through their protective systems, leading to additional outages. Loss of synchronisation of some generators may result from these outages or from operating conditions that exceed their excitation current limit.

(ii) The role of reactive power in maintaining voltage stability

Reactive power generation is the process of producing electrical power that does not transfer real energy but is crucial for regulating voltage levels, essentially acting as a mechanism to achieve and maintain voltage stability, meaning, by adjusting the amount of reactive power injected into the grid, operators can control voltage fluctuations and prevent voltage collapse. Whenever an imbalance occurs between reactive power demand and supply, large voltage drop is felt in the grid, leading to severe voltage sags or even collapse, especially in areas with heavy loads.

(iii) Reactive power influence voltage stability

Most electrical equipment act like an inductance, drawing reactive power from the grid, which can cause voltage drop, if not compensated. Power flowing through transmission lines also creates reactive power losses, further affecting voltage control.

(iv) Mitigation

Absorption and production of reactive power: Devices absorb reactive energy if they have lagging power factor (inductor-like) and produce reactive energy if they have a leading power factor (capacitor-like). By adding capacitors to the system, utilities can generate reactive power to counteract the inductive effects and maintain voltage stability. For maintaining voltage stability, power plants install equipment such as static VAR compensator (SVC), which are applied to inject or absorb reactive power as needed. Electric grid equipment units typically either supply or consume reactive power. Synchronous generators will provide reactive power if overexcited and absorb the same if under excited, subject to limits of the generator capability curve. Transformers will always absorb reactive power. Power lines will either absorb or provide reactive power. Overhead power lines will provide reactive power at low load, but as the load increases past the surge impedance of the line, the lines start consuming an increasing amount of reactive power. Underground power lines are capacitive, so they are loaded below the surge impedance and provide reactive power[9].

(c) Frequency stability:

Frequency stability refers to the ability of a power system to maintain steady frequency following a severe system disturbance such as occurrence of a fault in the transmission lines (with subsequent outage of the transmission line and the sudden loss of loads which were served through the line) or the sudden unexpected loss of a generator. This ends in a major imbalance between generation and load demands. It calls for the power grid's ability to maintain and restore equilibrium between system generation and load, with minimum unintentional loss of load. This is marked by sustained frequency swings, leading to tripping of generating units and/or loads.

9. Brief Analysis of Synchronous Generators and Inverters

(i) As seen above, both rotor angle and frequency stability are strongly tied to the dynamics of rotating mechanical components in traditional turbo generators. In contrast, the inverter and its power electronics in the IBR have no such rotating mechanical components. This means that we need a new set of equations to describe the functioning of these inverters to bring about a common platform for maintaining grid stability in a hybrid grid, to make both systems as similar as possible, since both are connected to the same grid. The variables inside inverter controllers which are similar to rotor angles are identified and linked using new software and/or hardware. In this way, a unique set of angles and frequency stability parameters can be identified, which will balance or synchronise both the spinning rotors of the turbo generators and the inverter angles in the electronics controls of the IBR.

(ii) Reactive power describes the background energy movement in an AC system arising from the production of electric and magnetic fields. Devices that store energy by virtue of a magnetic field produced by a flow of current are said to absorb reactive power; those that store energy by virtue of electric fields are said to generate reactive power. The flow of reactive power on the system will affect voltage levels. Unlike system frequency, which is consistent across the network, voltages experienced at points across the system form a 'voltage profile', which is uniquely related to the prevailing real and reactive power supply and their demand. For example, the obligatory reactive power service (ORPS) in the National Grid of the United Kingdom is the provision of mandatory varying reactive power output. At any given output, the generators may be requested by the grid authority to produce or absorb reactive power to help manage system voltages close to their point of connection. Generally, all transmission connected generators over 47 MW are required to have the capability to provide this service, as set out in the Grid Code, as per the 'National Grid UK - Reactive Power Obligatory Synchronous Generators'.

(iii) Both forms of generation have capabilities for producing reactive power, whose importance is briefly indicated above. However, the key issue is the geographical or topological locations of reactive power generation in a conventional power system grid versus the hybrid power system grid. In a hybrid grid, the IBR are well dispersed and need not be located near loads or at pitheads as in the case of turbo generators. For instance, anyone can install a small rooftop solar generator in one's residence and connect the same at low voltage to the local grid or interconnect it to similar generators in one's residential locality with or without tie-up to the local power grid. IBR are also connected at the medium or low voltage distribution levels (as dictated by the individual capacity) and some of them that are in GW range are connected to the grid through high voltage transmission lines. This means differing line impedance for each of these IBR is to be considered, which makes stability analysis complex. The control requirements will also become proportionally large and cumbersome.

10. Conventional Grid's Dependence on Inertia

(a) Conventional power plants that are powered by natural gas, coal, nuclear fuel, or hydro-power produce electricity with synchronous generators, which are perfect for the smooth operation of a power grid as they possess the following important characteristics[10]:

(i) The generators possess a natural tendency to synchronise with one another, which helps make it possible to restart a grid that has completely blacked out.

(ii) These generators have a large rotating mass, namely, their rotors. When a synchronous generator is spinning, its rotor, which is very heavy (for example, a typical rotor can weigh as much as 31 tonne in a Siemens-make 100 MW steam turbo generator – total weight being approximately 161 tonne) cannot come to rest swiftly[11]. This huge rotational kinetic energy needs to be absorbed as the rotor slows down. This is termed as generator's inertia. Even a bicycle develops inertia as we start to pedal, and to stop the bicycle, we have to stop pedaling while simultaneously applying brakes. The amount of inertia in a grid determines how fast a power grid will respond to maintaining the grid frequency, whenever a failure occurs.

(b) The importance of inertia

Whenever a large generator trips, there occurs a deficit in supply and the balance between load and generation in a grid is lost. This calls for production of more power to reset this balance. The loads tend to extract rotational energy from healthy generators. This slows down the healthy machines too. Thus, the overall grid frequency starts to decline. In this way, grid frequency is affected, as the rotational speed of generators start declining in the grid. However, the kinetic energy stored in the rotating mass slows this rate of decline in the frequency. This also gives healthy generators time to increase their power output to compensate for the loss of the affected generator. Electricity grids are designed so that even if the largest generator running at full output stops, the other generators can pick up the additional load and the lowest frequency is never left to fall below a specified value[10,12].

11. Effects of Inertia on a Power Grid

Inertia is one of the chief variables that regulate frequency response in a grid. Inertia is defined as the tendency of an object in motion to remain in motion, unless acted upon by an external force as per Newton's First Law. From age-old times, inertia has acted as an important source of reliability in an electric grid. Inertia from rotating electrical generators in fossil, nuclear, and hydro-electric power plants represents a vital source of stored energy that can be tapped for a few cycles to provide the grid valuable time to respond to sudden tripping of a power generator (loss of generation) or other system faults and failures, resulting in loss of loads. In a typical power grid, inertia is derived from the many generators that are synchronised, meaning all generators are rotating in locked step at the same frequency[10,12].

12. IBR's Fast Response can Compensate for its Lack of Inertia

(a) Grid frequency, which is a measure of the balance of supply of electrical energy and demand (loads) can drop, in case a large power generator or transmission fails (loss of load). Inertia resists this drop in frequency, giving time to the grid to re-balance supply and demand.

(b) It is seen that a grid derives its inertia from synchronous generators, which, being rotating machines, have customarily slow response times (But nowadays their response time is improved with advanced exciter systems and power electronic controls).

(c) A grid with predominantly slower response generators needs more inertia to maintain grid stability compared to a grid with fast response. This is because slower response generators need more time to cope with changes and they get this additional time through additional inertia.
(d) A grid with IBR can quickly detect and respond to grid disturbances providing faster frequency response. This will reduce the need for more inertia.
(e) Whenever an IBR replaces a synchronous generator, the system inertia is reduced, but at the same time, the fast response from IBR compensates for such loss.
(f) The importance of inertia to a power system depends on many factors, including the size of the grid and how quickly generators in the grid can detect and respond to imbalances.
(g) Using power electronics, IBR, including wind, solar, and storage systems can quickly detect frequency deviations and respond to system imbalances. Tapping into electronic-based resources for this 'fast frequency response' can enable response rates faster than traditional mechanical response from conventional generators, thus reducing the need for large inertia.
(h) Replacing conventional generators with IBR offers two neutralising results: (i) The above resources do decrease the amount of inertia available. (ii) At the same time, these resources can reduce the amount of inertia actually needed (as their speed of response is quick). This advantage balances to some extent the loss of inertia.

13. Frequency Stability in a Grid

Frequency stability in a grid is affected by a number of variables apart from inertia. In fact, there are two major classes of inertia in a grid. These are generator inertia and load-side inertia. The other variables apart from inertia are magnitude of the fault, limits set in under-frequency relays, and speed of frequency response controllers. These aspects are briefly discussed below:

(a) Generator inertia:
Units of energy and inertia: Electrical energy is most commonly measured in terms of the amount of power (measured in watts) delivered over some period of time (typically an hour). The most common units are kilowatt-hours (kWh), megawatt-hours (MWh), and gigawatt-hours (GWh). The inertia of a generator is described in general in terms of stored rotational kinetic energy, so inertia has the same units of energy[13] (power delivered over a period of time).
For example, a generator with 1 GW of inertia can deliver 1 GW of power for 1 second from its stored energy. 1 GW is equal to 0.27 MWh or 278 kWh.
A typical 100 MW generator has about 0.4 GW of stored energy, or about 110 kWh, while the kinetic energy stored in a large 1,000-MW generator is ten times more (about 4 GW).
Doubling a grid size results in increasing the grid inertia by a factor of 2. Thus, in a larger grid, there is more available time to rectify disturbances or imbalances. A generator has to be on-line (connected to the grid and functioning) for its inertia contribution available to the grid. A generator's inertia is independent of its power output. A generator provides the same amount of inertia throughout its operating range. For example, a committed (evacuating to grid) synchronous generator rated at 500 MW provides the same amount of inertia when it is generating 250 MW as when it is generating 500 MW. The combination of inertia constant and total capacity of online generators determines the total inertia provided by the generators.

(b) Methods to increase grid inertia:
(i) One of the ways to increase the grid inertia when the traditional generators are replaced by IBR is to connect IBR that use synchronous generators (hydropower, geo-thermal, concentrating solar power [CSP]) and other non-renewable low carbon sources of energy like nuclear and fossil plants with carbon capture. In addition, conventional energy storage systems involving pumped storage systems and compressed air systems that use synchronous generators or motors or whose loads comprise synchronous motors can also be connected to the grid. Thus, a judicious mix of sources can help in stabilising the grid.
(ii) The use of synchronous condensers to increase inertia: Synchronous condensers are actually synchronous motors (without load), which draw energy from the grid to maintain a spinning mass (its rotor), and when required, can inject power into a grid similar to a synchronous generator. They serve well in maintaining voltage levels in local grids and they also instantaneously absorb reactive power peaks, for example, when large cold rolling steel mills are accelerated to their rated capacity.

(c) Load inertia and load damping:
(i) Load inertia effects: Loads, their magnitudes, and their types are important for analysis in a grid. So far, we have been discussing generators' inertia. The inertia exhibited by loads is also an important criterion to be factored in our approach. 'Load inertia' refers to the ability of large motors and other electrical loads to resist sudden changes in frequency by drawing slightly more or less power when the grid frequency fluctuates, essentially acting as a temporary energy reservoir that helps stabilise the system during disturbances like power plant failures, providing valuable time for grid operators to respond and re-balance supply and demand. This behaviour is primarily due to the stored kinetic energy within rotating machinery like

large industrial motors. When the frequency of a traditional power system changes under a power imbalance, the energy stored in the electro-magnetic fields and rotating masses of the system loads, such as asynchronous motors, change to resist the change in the system frequency; this is called the load inertia effect. Therefore, the frequency characteristics of a load are typically used to describe its effect on the system frequency[10,12].

(ii) Load damping effects: Load damping is about how a load responds to changes in frequency. It is an important factor in the frequency response of a system. This involves two factors: the inertia of loads and the change in actual energy demand as a function of frequency. When power is switched off, an electric light shuts off instantaneously. However, we notice that in the case of an electric ceiling fan, it will continue to turn for some time even after it is switched off. This represents inertia similar to that in electric generators. Certain types of motors add inertia to the grid. Another impact results from the actual change in electric demand that happens with changes in frequency. In our previous examples, it was assumed the load remains constant after the contingency event. However, for some loads, including many motors used in industrial processes, the actual electricity demand will decrease at lower frequencies. For example, a decreased amount of power is needed to operate a car at a speed of 60 km/h compared to a speed at 80 km/h.

(iii) Load damping constant: Any sudden increase in load will decrease the system frequency and a sudden decrease in load will increase the frequency[14]. The damping constant is a value that describes the relationship between changes in frequency and load. The damping constant is the percentage change in load for a 1 percent change in frequency. For example, a damping constant of D-2 means that a 1 percent change in frequency will result in a 2 percent change in load[15]. The load-damping characteristic models show how a load responds to frequency deviations. It is usually considered a constant, but it can be obtained from operational experiences or load models[16].

For instance, in the US, a typical estimate is that a 1 percent decline in frequency will reduce load by 1-2 percent (meaning a damping constant of between 1 and 2). However, this effect is expected to lessen over time as older 'inertia-providing' large motors in the industries are replaced with energy efficient motors and with motors that are specifically designed to operate from variable-speed power supply systems.

(d) Contingency size: A key factor
A large contingency produces a much faster rate of frequency decline, resulting in the frequency dropping fast. Alternatively, if a contingency is minor, the frequency would drop more slowly, giving the system more time to respond.

(e) Under frequency limit settings (UFLS settings):
Loads are shed to save the grid from black-out, based on setting selected in an under-frequency relay. The power system's UFLS settings represent the final main element determining how much time is needed to respond. UFLS is initiated by frequency counters that monitor frequency and automatically disconnect certain parts of the grid (rapidly and without warning) if the frequency drops below a certain setting. UFLS actually use multiple settings that progressively shed more and more load as frequency drops lower and lower. The basic idea is that a relatively small amount of load is shed at the initial stage of under-frequency. The system is monitored to see whether this is enough to correct the imbalance with minimal impact on consumers. However, in case the imbalance is not corrected, further but additional load shedding occurs till the frequency decline is corrected. Only in extreme cases, the entire grid gets shut down[10,12].

(f) The role of primary frequency response:
Grid operators use a variety of processes that can respond to events, which change the frequency to maintain grid frequency and apply sparingly the UFLS, and thus, avoid load shedding to the extent feasible. This is achieved through the application of the primary frequency response (PFR) system. PFR detects changes in frequency and automatically – without action from the system operator – adjusts operations of online generators to maintain frequency within the desired range. PFR refers to the automatic, immediate adjustment of power generation by grid operators to maintain system frequency stability when disruptions occur. This is similar to 'cruise control', which is provided in today's automobiles. Similarly, in the grid too, there may not be any immediate need for manual intervention from system operators. It is the first line of countermeasure against frequency fluctuation. PFR activates rapid response from generator governors to offset the change in the frequency. In addition to this, PFR acts to increase power from the remaining generators and (temporarily) compensate for the energy lost from a failed generator. Providing PFR calls for the installation of an active modern governor in the generators. Also, the generators will be operating at less than full output (which means that provision of headroom to increase output). Upon a decline in frequency, generator governors detect this change and act to open valves and take other actions, which will increase the flow of fuel, steam, water to generator turbines. This increases the power produced, but this process takes time, much as it takes time for a vehicle to accelerate after a driver presses the accelerator[12].

14. Need for Suitable Inverters

(a) Primary role of inverters in IBR:

The conventional synchronous generators produce AC electricity. While wind turbines, PV-based solar power plants, and battery-storage plants produce DC electricity. Among the DC electricity generators, only wind turbines are equipped with rotating machines to deliver the output. Wind turbines are not synchronous rotating machines, when viewed from the grid. These machines produce AC electricity but in frequencies that are decided by the prevailing wind speed. This variable-frequency AC is rectified first into DC power supply. This DC power supply is in turn inverted into AC electricity with frequency to match with that of the grid. In the case of PV solar plants and battery storage plants, the rectifier portion is not applied but a DC link circuit is used. However, the change from DC circuit to AC power in grid frequency is carried through an inverter circuit[18,21,22].

(b) Functioning of inverter:

(i) Introduction

In an inverter, power switching devices such as transistors, thyristors, MOSFETs, IGBTs are used, which rapidly switch the polarity. By switching at high speed, the inverter produces a high-frequency AC signal, which is subsequently filtered by a combination of resistors, inductors, and capacitors to produce a smooth AC power output. In an inverter, switching speed is controlled by many techniques, including the well-known pulse width modulation (PWM) system. The controlling signal generated by a microcontroller, which determines the 'on' and 'off' times of the switching devices, allowing accurate adjustment of the switching frequency, which determines the quality of the output wave. The width of the pulses in the PWM signal is varied to control the average output voltage and frequency in an inverter[18,21,22].

(ii) Comparison with synchronous generator controller

In contrast, in a conventional synchronous generator, the output waveform comprising voltage and frequency are controlled through AVR and rotational speed of the rotor, respectively. Voltage is controlled through the generator's excitation, which is the principal function of an AVR, which have different control modes such as droop and cross-current compensation. Power input to the turbine is varied through governor control, which essentially regulates the speed of the rotor.

(iii) Faster response from electronic controls

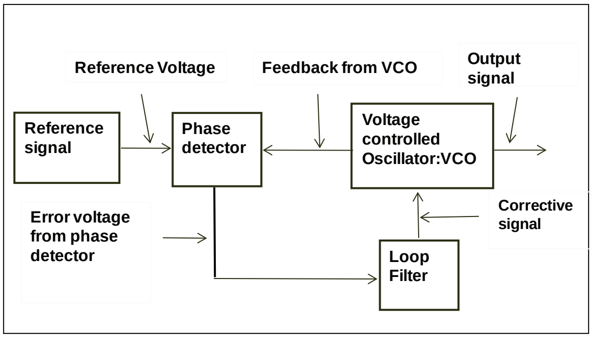
From the above discussion, it may be noted that inverter controls that are electronic are faster than the classic controls (basically electro-mechanical systems and the associated time constants in changing the field flux and governor operation) used in synchronous generators[18,21,22].

(iv) Difficulties encountered in grid following (GFL) inverters

GFL inverters need a voltage reference for their synchronisation with the grid. They obtain this reference from the grid to which they are connected. The controllers in the GFL inverters sense the frequency of the voltage waveform and lock onto the same. Thus, their operations are possible so long this voltage reference is available. In case of grid black out, the inverters will stop sending out power to the grid, as the voltage reference is missing.

Commonly, a phase-locked (PLL) controller is included for achieving synchronissation with the grid. It is a closed-loop feedback control circuit, which is frequency- as well as phase-sensitive. It may be noted that even when two signals have the same frequency, their peaks and troughs may not occur in the same moment or place. This means that they do not reach the same point on the waveform at the same time, termed as 'phase difference'. It is measured as the angle between the grid voltage and the inverter output voltage. For signals with varying frequencies, the phase difference between them will always vary, which means that one signal will lag or lead the other by a varying amount. A PLL reduces phase errors between output and input frequencies. When the phase difference between these signals is zero, the system is said to be 'locked'. And this locking action depends on the PLL's ability to provide negative feedback, applying the output signal back to the phase detector. A typical PLL controller comprises: (a) Phase detector (b) Voltage-controlled oscillator and (c) low pass filter, as shown in Figure 3. In addition to synchronising the output and input frequencies, a PLL also helps establish the input-output phase relationship to generate the appropriate control voltage for successful power evacuation from the IBR. Thus, it helps achieve both frequency and phase lock in a circuit[18,21,22].

Figure - 3 - Typical Block Diagram of PLL control



Credit-https://oldsite.pup.ac.in

It may be seen from Figure 3, phase detector evaluates the difference between the reference signal and the feedback signal from VCO. The phase detector measures the difference in phase signals and sends a proportional signal to the low pass filter, which produces a signal, whose duty cycle is proportional to the phase difference between the two inputs. The error signal generated by the filter sends a DC signal to VCO for controlling its output frequency[17].

(v) Limitations in a GFL inverter

GFL inverters work without any interruption, so long fewer inverters are connected to a grid. But when the numbers become large, for example the level of inverter power increases beyond, say, 60 to 70 percent of the grid capacity, the operations of these inverters get complicated, as grid frequency stability becomes difficult to control. For this reason, power grid operators are restricting the connection of too many inverter power resources to their grid. For instance, the Electric Reliability Council of Texas (ERCOT) in the US regularly curtails the use of RE in their province because of stability issues arising from a high number of grid-following inverters. Whenever the number of inverter-based power sources on a grid becomes high, the inverters should have the capability to support grid-frequency stability, and they should on their own, form the reference voltage and frequency of the grid. Grid forming inverters (GFM) exhibit this capability[18].

(vi) The similarity between GFM and GFL inverters

GFM and GFL inverters have similar capabilities. Both have the capacity to inject current into the grid during a disturbance. Also, both types of inverters can support the voltage on a grid by controlling their reactive power. Both inverters can also help maintain the frequency on the grid, by controlling their active power.

(vii) The difference between GFM and GFL inverters

The software makes the main difference between these two types of inverters. GFM inverters are modified GFL inverters that are currently undergoing tests for its suitability for operations in large grids. Its suitability for micro-grids has been tested and found to be satisfactory. The GFM inverter is controlled by a special operating system, which is programmed to keep a firm output voltage waveform. However, it also allows the magnitude and phase of that waveform to change over time. This means that GFM inverters hold a constant voltage magnitude and frequency on short time scales (for a few cycles measured in milli-seconds) while allowing its magnitude and frequency to change over several seconds (large number of cycles) to synchronise with other nearby sources in the grid, like traditional synchronous generators[18,21,22].

(viii) Response with respect to time scale[18]

- In *sub-transient* time scale: GFL control provides constant current output for P/Q control; GFM control provides constant output voltage for v/f control.
- In *transient* time scale: GFL control provides active and reactive power control; GFM control provides voltage and frequency control.
- In *steady-state* time scale: Both controls follow droop characteristics.

(ix) Comparison of inherent design aspects

GFL inverters depend on grid strength and cease to operate in island mode and do not possess black start ability. GFM inverters continue their operation in a grid even without the customary synchronous generators and possess intrinsic black starting ability.

(x) Virtual synchronous machines and droop curve controllers

GFM inverters are programmed to mimic synchronous generators. These are called 'virtual synchronous machines (VSM)', which achieve this response by mimicking the physical and electrical characteristics of synchronous generators, using control algorithms that shape its response. In another variation, GFM inverters are programmed to just hold a constant target voltage and frequency, allowing the target voltage and frequency to change slowly over time to synchronise with the rest of the power grid, following what is called a droop curve. 'Droop control' in a generator refers to a control method where the output frequency of a generator slightly decreases as the load on it increases, allowing multiple generators to share power proportionally based on their capacity when operating in parallel on a grid. Essentially, each generator 'droops' in frequency as it takes on more load, enabling a stable power distribution across all generators involved. The droop action control strategy is based on the principle that the generator with the lowest frequency will have the highest load, and the generator with the highest frequency will have the lowest load[19]. These are discussed in the later part of this paper.

(xi) Comparison of operation of GFM and GFL inverters on a short circuit fault in a grid

Case of GFM inverters: Let us suppose that a transmission line shorts to ground or a generator trips due to a lightning strike. The key advantage of a GFM inverter in such a situation is that it does not need to quickly sense frequency and voltage decline on the grid to respond. Instead, a GFM inverter just holds its own voltage and frequency relatively constant by injecting whatever current is needed to achieve that, subject to its physical limits. In other words, a GFM inverter is programmed to act like an AC voltage source behind some small impedance as already discussed (Refer to Figure 2). In response to an abrupt drop in grid voltage, its digital controller increases current output by allowing more current to pass through its power transistors, without even needing to measure the change it is responding to. In response to falling grid frequency, the controller increases power input to the grid similar to a synchronous generator[18,21,22].

Case of GFL inverters: In the case of GFL inverters, measurement of the change in voltage or frequency has to be made prior to taking a suitable action, such as adjusting their output current to cushion the change. This kind of response will work when faults are smaller and very fast action is not needed. However, when the grid becomes weaker with very less voltage sources nearby, GFL controls tend to become unstable. As they start measuring the voltage and adjust their output, the voltage has already changed significantly and fast injection of current at that point is needed, which can create an unstable positive feedback signal. Increased population of GFL inverters reduces grid stability, as it becomes more time consuming to stabilise the vast numbers of inverters. This slow response may lead to grid black-out in some cases.

(xii) Can an inverter produce additional current without self-damage?

It is possible that the inverter current output can be increased for a short period in response to a fault in the grid. However, its electronics do not allow such an increase unless they are well within the limits. This is to ensure that no damage is done to the solid state switching devices as they have to dissipate additional heating when large and sudden increase in current takes place. Therefore, a mere increase in current is ruled out without increasing the rating of switching devices with attendant cost increase. In comparison, a synchronous generator can provide approximately 5-7 times its rated current for a short period of several cycles without damaging itself. In standard design, inverters cannot sustain current surges beyond 1.1-1.3 times above their steady state rated current.

(xiii) Population of GFM and GFL inverters in a hybrid grid

In a hybrid grid which is dominated by inverter-based generation, all inverters need not be GFM type. We just need enough GFM inverters to strengthen the grid so that GFL inverters remain stable. Depending on the grid characteristics, its size, and the number of inverters connected, it is felt that at least 30 percent of power generated will be through GFM inverters as per current research. This figure is likely to change with more research work progressing in this aspect[18,21,22].

15. Protection systems in a hybrid grid

(a) Apart from the stability criteria briefly discussed above, we have to analyse the challenges in providing protection systems in a hybrid grid. The problem faced here is as follows: The conventional grid (without IBR) protection design is based on high fault currents, which are mainly contributed by synchronous generators. Some of the advantages with high fault currents are fast and accurate detection, high speed in isolating the faulty equipment, and associated low costs to achieve the above. In contrast, IBR provides much lower fault currents. Also, the same fault current phasors as produced by a conventional system are not produced. Oversizing certain components in the inverter, an IBR can be made to provide more fault current. Certain IBR, such as concentrating solar power, biomass, or geo-thermal that use turbogenerators, can produce high fault currents as in a conventional grid. Thus, it is possible to design a judicious mix of IBR to get a reasonably high fault current[20].

(b) In general, faults occur when two phase conductors touch (termed as line to line fault), or when a tree falls on a live conductor (line to ground fault). Due to low fault impedance in these cases, huge fault currents flow, which are supplied by generators. This is monitored by the protective system, which trips the relevant circuit breakers and isolates the faulted area. The philosophy of protection relays vary as per magnitude of fault current. For instance, for low fault current systems, differential protection, highly sensitive phase over current relays, highly sensitive earth fault relay protection, negative sequence protection systems backed up by accurate measurement of current levels through employment of accurate current transformers, fast coordination with upstream relay systems and application of high speed processors. In general, it may be seen that the cost of providing protection in low fault current systems are generally higher than the cost incurred in high fault level systems [21].

16. Brief Comparison of Responses from Synchronous Generators and Inverters

(i) Inertial response:

Synchronous Generators have inherent inertial response based on rotating mass and electrical characteristics of the machine, which act to overcome any imbalance between power supply and demand. This response is automatic and occurs without any external prompting.

Inverters do not have such in-built inertia response; but the fast frequency response characteristic of an inverter can reproduce (duplicate) the inertial response in synchronous generators based on simulation models in their controllers.

(ii) Frequency response:
In synchronous generators, this is achieved through frequency sensing governors. Usually, this takes multiple seconds for a full response.
In inverters, this is provided through frequency sensing by fast sensing microprocessor-based relays, which can be programmed to sense and act in less than a second.

(iii) Voltage control:
In synchronous generators, this is achieved through an automatic voltage regulator (AVR) controller. AVR senses the generator's terminal voltage and adjusts the generator's excitation current to maintain a constant terminal voltage.
In inverters, this is provided by sensing a voltage reference from other generators. Moreover, advanced (grid forming) inverters can independently provide voltage reference and control.

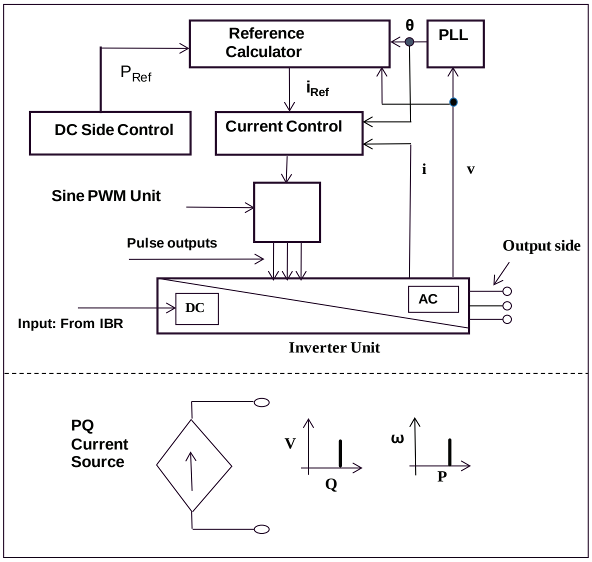
(iv) Fault current:
Synchronous generators can provide about 5-6 times their rated current for a very brief period of time. The copper wires and magnet systems can handle such large short circuit currents without damage for a very limited period of time.
In inverters, it is not possible to provide such high fault currents even for brief periods. Their electronic hardware typically limits the fault current to about 1.5 times rated current to prevent overheating and eventual burning out of the components, which are highly sensitive to temperature increase. However, it is possible to increase this limit but at an exorbitant cost of increasing the ratings of the electronics hardware [21]. In IBR dominated grids, the fault current is low (when compared with traditional or hybrid grids) as the inverter currents are limited (see below). Efficacy of conventional protection schemes, which from the early days relied on high fault currents, needs urgent review and reset[21.1].

(v) Current limiters
In the case of IBR, current limiters are employed as defense against grid disturbances. These are carried out in three variations, In the 'direct current limiting' technique, the output current of the inverter is fixed and cannot increase beyond the preset value. In 'indirect current limiting' technique, the voltage and power reference values are adjusted to reduce the current flow in case of fault. In 'hybrid current limiting' technique, both direct and indirect current limiting settings are employed to limit the current. The design and implementation of current limiters is complex as it affects grid steady state stability, transient stability, voltage and reactive power support, post-fault recovery, and grid re-synchronisation[21.1].

17. GFL Inverters in IBR

As indicated in Figure 4, the grid-following controller contains two main subsystems[22]:

Figure-4: GFL Inverter Block Diagram



Courtesy: NREL - 73476.pdf

- A phase-locked loop [PLL] controller that estimates the instantaneous angle of the measured converter terminal voltage and
- A current control loop that regulates the AC current injected into the grid.

The PLL provides the angular reference of the current commands and carries out the 'following' behavior. The grid-following AC terminals mimic a current source, whose real and reactive output tracks the references. For fixed power commands, an inverter acts like a constant real-reactive power (PQ) source. This control strategy is called grid-following because its functionality depends on each inverter having a well-defined terminal voltage that its PLL can latch-on to and follow. The system voltage and frequency are regulated by power supply resources, which are external to each grid-following inverter. As the number of grid-following inverters attached to a grid increases, additional functions that preempt excessive voltage and frequency deviations, which are called grid-support functions, are provided in the controller. Currently, almost all IBR work with grid-following controllers.

18. GFM Inverters in IBR

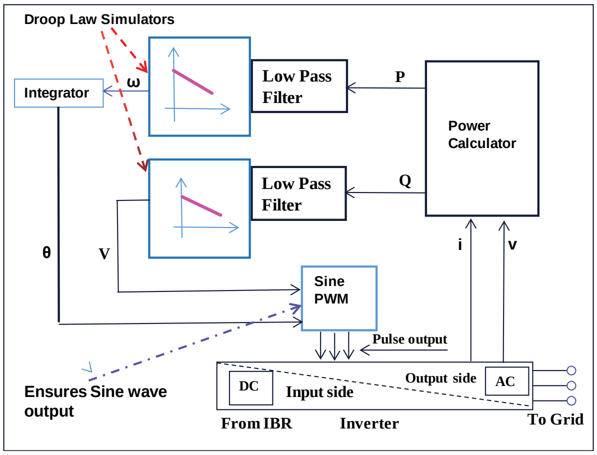
Many types of grid-forming strategies have been developed over the past 20 years. In general, the term 'grid forming' is attributed to any inverter controller that regulates instantaneous terminal voltages and, at the same time, stays connected together with other grid-following and grid-forming inverters and synchronous generators on the same grid. A GFM inverter is not provided with PLL controls.

GFM controllers are different from GFL controllers, which act as current sources, require a PLL, and always need to reference an externally regulated voltage. GFM controllers do not need any external communication or signaling to operate. In principle, GFM inverters must allow for the realisation of scalable and de-centralised AC power generation systems, whose system voltages and frequency are regulated by the interactions of the GFM inverters themselves. It can be observed that a synchronous generator fulfills all the above requirements in general and makes an ideal GFM inverter. Thus, the need is for a GFM inverter, which emulates the merits of a synchronous generator and, at the same time, has the speed and adaptability of power electronics and controls[21,22,28].

To achieve the above goal, GFM inverters are programmed to mimic or act as droop controllers or virtual synchronous machines or virtual oscillator controllers, as shown respectively in Figures 5, 6, and 7. These are discussed briefly below:

- Droop control:
  The most well-established grid-forming method is droop control, which was first proposed[22,23] in the early 1990s. In droop control, a linear trade-off between frequency and voltage versus real and reactive power takes place, similar to the operation of a synchronous generator in steady state. These so-called 'droop laws' are referred to as the P-ω (real power-frequency) and Q-V (reactive power-voltage) relationships, and they exhibit the following properties:
  - System-wide synchronisation: All units reach the same frequency.
  - Power sharing: Each unit produces power in proportion to its capacity (as per its droop slope, which can be preset).
  These properties arise as a result of the interactions from the grid and locally programmed droop laws.

Figure-5: Droop Control Block Diagram



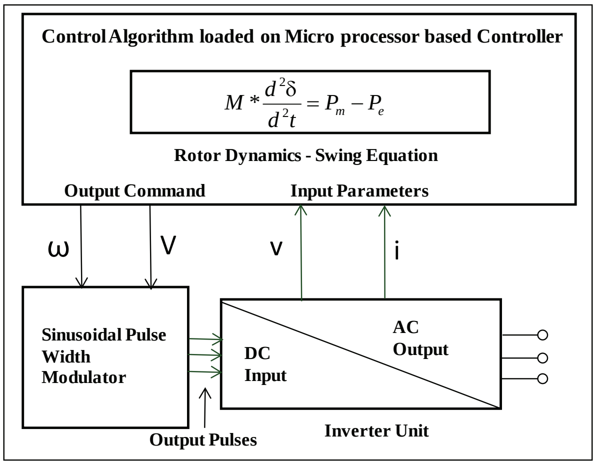
Courtesy: NREL - 73476.pdf

Droop based control with active and reactive power. Regulation of both active power (P) and reactive power (Q) outputs are based on the deviation of system frequency and voltage from desired set points.

Droop based control with voltage (V) and frequency (w): Here, the inverters output voltage and frequency are adjusted in response to changes in load or grid conditions.

- Virtual synchronous machines (VSM):
  This method imitates the response of a synchronous generator with adjustable inertia, gain and damping characteristics. This approach is based on the emulation of a synchronous machine within the controls of an inverter[24,28]. Specifically, inverter terminal measurements are fed as inputs into a digital synchronous machine model whose emulated dynamics are mapped to the inverter output in real time. The various types of virtual machine controls can vary greatly from detailed electro-mechanical models to simplified swing dynamics algorithms. Programmes which closely match machine characteristics have both Q - V and P - ω characteristics and are often named as 'synchronverter'. These provide synthetic inertia. In another model, 'virtual inertia methods' can also be programmed. These are simpler than virtual machine control and follow only the dynamics of a rotor model and its steady-state P - ω droop. Figure-6 shows a typical VSM model[22].

Figure- 6: Virtual Synchronous Machine

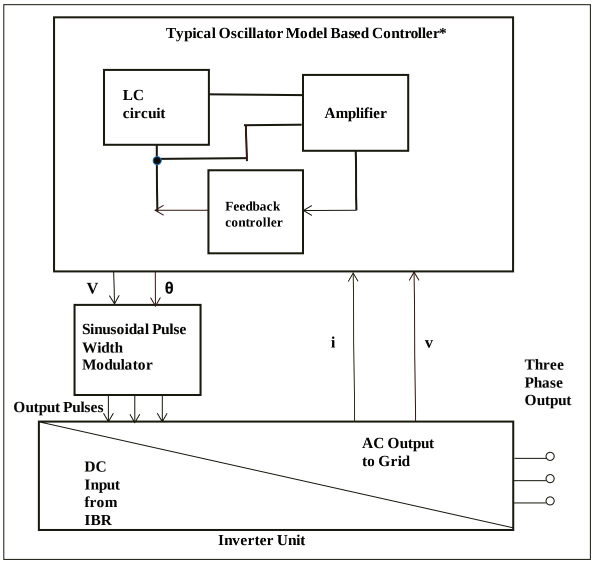


Credit: NREL - 2023 - Grid Forming Inverters

- Virtual oscillator controllers:
  In recent years, yet another inverter control method based on the emulation of non-linear oscillators has emerged. Like in the case of a virtual synchronous machine, real-time measurements are fed into a software model, whose output variables control the inverter power stage. The model is programmed as an oscillator circuit, whose natural frequency is the nominal

AC grid frequency, and its remaining parameters are tuned to adjust the nominal voltage and control bandwidth. The virtual oscillator model obeys Q - V and P - ω droop laws in steady state. Figure 7 shows a typical oscillator-based model[22,25].

Figure - 7: Virtual Oscillator Controller



Credit: NREL - 73746.pdf &
*** Tutorialspoint.com - oscillator circuit htm**

- Similar characteristics exhibited by various grid-forming controllers:
  Despite the differences in the hardware and software between droop controllers, virtual synchronous machines and virtual oscillators, all these techniques have similar response characteristics. The output terminal behaviour of an inverter with any of the above discussed grid-forming controllers resembles a voltage source with an amplitude and frequency that varies with reactive power generation and the system load respectively. This characteristic allows grid-forming inverters to adjust output power nearly instantaneously to balance loads, regulate local voltage, and contribute to frequency control. Although grid-following inverters can be programmed to emulate the aforementioned properties, they still require a well-defined terminal voltage as a reference, which is absent when the grid goes down. At present, grid-forming inverters are employed and are operating successfully in micro-grids and in off-grid installations that require high reliability[28].

As GFL inverters employ simple controls, they are less expensive than GFM inverters. They can also achieve faster response, provided they are connected to a stable grid. In comparison, it is necessary to provide more elaborate and additional control systems in GFM inverters.

19. Software Analysis of the Models

Droop-based GFM model (REGFM_A1) and virtual synchronous machine GFM model (REGFM_B1) are now available in commercial positive-sequence tools. This helps the system designer with various options.

20. Weak and Strong Grid Conditions – Comparison of Operations of GFL and GFM Inverters

Let us now see the dynamic response to a grid event (fault or addition of a generator or loss of a generator or load) and the small-signal behaviour under weak or stiff grid conditions. A weak grid is distinguished by high impedance, susceptibility to voltage fluctuations, and possessing a low short circuit ratio (SCR less than 2.0) while a strong (or stiff) grid possesses low impedance coupled with strong voltage regulation and SCR above 3.0.

SCR is defined as the ratio of short circuit MVA at a source bus to the MW rating of the generator connected to that bus. High SCR signifies the source is 'small' relative to the rest of the network. In such a case, any loss of one of the source generators will not impact the operations of the grid. When the value of SCR is low (weak grid), the source generator rating is comparable to that of the network. Here, any loss of a source generator is a major event, which will eventually upset grid operations [26,27].

Thus, the recovery can be made faster and easier in a strong grid. GFL inverters also perform better in a strong grid. However, GFM inverters have inherent codes to perform well in both weak and strong grids.

When a change occurs in grid voltage, the GFL inverter control attempts to maintain the injected current phasor by allowing the voltage phasor to respond accordingly. In the GFM inverter control, the voltage phasor reference is primarily maintained, and the inverter current responds accordingly to satisfy the power injection constraints. This dynamic behaviour is more desirable and brings out a stable platform whether critical functions can be performed to keep the grid stable [26,27].

21. Implementation of GFM Inverters and Challenges

Retrofitting older inverters is difficult. As discussed earlier, it is recommended that a minimum number of GFM inverters are connected to a hybrid grid to bring in stability. It is also found that GFM inverters, paired with energy storage, offer full capabilities, especially during grid blackouts. When a GFL inverter is converted to a GFM inverter, the control algorithms can be implemented as software changes. Some working inverters can be re-booted with changes to migrate to the mode of operation of GFM inverters. However, the crucial black start capability may require additional hardware and programming. In practice, it is found that it becomes difficult to retrofit older GFL inverters with new control software, as the new software may require more processing power, memory and RAM. It will be ideal to place about 25-30 percent grid forming inverter-based resources in the weak parts of the grid to increase grid stability, as per current research work[27].

Recommendations for successfully integrating higher levels of inverter-based variable renewable sources (wind and solar) in an existing hybrid or a conventional grid[27]:

(a) It will be ideal to make sure all new large IBR are responsive and help support stability. GFL IBR needs to follow the standard IEEE-2800 *(IEEE Standard for Interconnection and Interoperability of Inverter-Based Resources [IBR] Interconnecting with Associated Transmission Electric Power Systems[29])*.

(b) Installation of a new battery system-based IBR with built-in GFM capability, which will help achieve higher IBR penetration in the grid and to maintain or increase grid stability.

(c) Provision of additional storage, as this will help in turning off conventional generators currently running at minimum load for giving support to a conventional grid, whenever a blackout occurs.

Additional notes on battery-backed storage:

The storage capacity needed to stabilise the system depends on its physical location. It has been found from the case study, the capacity can be less when connected closer to the region with lots of IBR connected. The longer the electrical distance (that is factors such as physical distance, actual route length, and medium like cable or overhead lines) between the storage and the IBR, the more storage capacity is required to ensure stability of the IBR and the grid. The control in the present day GFL inverter is designed to work properly as long as the grid voltage is insensitive to inverter current injection. At a weak grid location, the PLL may fail to lock onto the grid frequency following a disturbance, resulting in an inverter injecting current at an incorrect phase. GFM controls incorporated storage system boosts the grid strength so that the conventional GFL based inverter controls can also work with stability[28].

22.Note on IEEE Standard no 2800-2022

Uniform technical minimum requirements for the interconnection, capability, and lifetime performance of inverter-based resources interconnecting with transmission and sub-transmission systems are established in this standard. Included in this standard are performance requirements for reliable integration of inverter-based resources into the bulk power system, including, but not limited to, voltage and frequency ride-through, active power control, reactive power control, dynamic active power support under abnormal frequency conditions, dynamic voltage support under abnormal voltage conditions, power quality, negative sequence current injection, and system protection. This standard also applies to isolated inverter-based resources that are interconnected to an AC transmission system via dedicated voltage source converter high-voltage direct current (VSC-HVDC) transmission facilities; in these cases, the standard applies to the combination of the isolated IBR and VSC-HVDC facility, and not to an isolated inverter-based resource (IBR) on its own[29].

23. Note on UNIFI Consortium

Universal interoperability of grid forming inverters – NREL, University of Texas-Austin, and EPRI[30]

The UNIFI Consortium addresses the challenges of integrating grid-forming (GFM) technologies into electric power systems with three major focuses:

- Research & Development
- Demonstration & Commercialisation
- Outreach & Training

Started in 2022 by the Department of Energy in the US, UNIFI is focused on bringing the industry together to unify the integration and operation of inverter-based resources and synchronous machines.

Some of the UNIFI models:

WECC: Offers droop based GFM model (REGFM_A1), which is available in four commercially available positive sequence tools, such as PSS/E, PSLF, Power World and TSAT.

PSCAD: Support electromagnetic transient [TMT] models of PV inverter-based resource in GFL and GFM mode.

EMTP. Generic EMT programme [EMTP] model for a three-phase aggregated GFM inverter.

24. Note on Black Start with IBR

(a) Black start in a power grid:

Black start means restarting the generators in a grid after a large outage, which practically switches off the grid. Black start capability is highly indispensable and the same is usually provided by grid connected synchronous generator-based power plants. A black start capable power plant must have reserve auxiliary power on-site (presumably from a grid-independent source like diesel or gas-based generators) to provide start-up power to the plant in its islanded condition. The auxiliary power supply will have sufficient real and reactive power capacity to energise necessary transformers, lines, and customer loads, which it is specified to start, and reserve energy capacity (or fuel storage) to operate for the duration specified by the grid operator. More essential is that such plants will have minimal and fast start-up time as the grid cannot be left without power for a long period of time[31].

(b) Need for utilising new resources for black start in a hybrid grid:
The electricity grid is changing with an increase in the number of IBR, such as solar, wind and battery systems. This trend is bound to increase further due to the falling cost of solar and wind. Energy storage is also being added to the grid at a rapid pace in part to balance the intermittency of renewable sources and is well positioned to provide emergency services, such as black start. While renewables are being added to the electricity grid, synchronous generators are being retired[31].

(c) Challenges for IBR in providing black start services:
These are chiefly[31]:
(i) Differences between the behaviour pattern of inverter-based resources and traditional synchronous generators
(ii) Power system architecture and control requirements, which are further discussed below.
1) All IBR have less over-current capacity than similarly sized synchronous generators, which can affect their ability to black start loads with high in-rush, like motors and transformers, and limit their fault current contribution.
2) Renewable IBR have intermittent supply, which limits their ability to be available all the time for providing black start power. In present times, renewable solar power (solar PV)-based IBR are ordered together with suitable sized storage systems (mandatory). Such storage systems are meant to be used to restart the system subject to budget availability and/or constraints.
3) Traditional black start resources are large and centralised while battery and solar resources are often distributed geographically and mostly connected at the distribution levels near their locations. This calls for detailed power system studies to arrive at optimum operating procedures to employ them as black start resources, including their location and size, which was discussed earlier in this paper. Paralleling multiple IBR is tried sometimes as the available fault current can be increased. However, changes in protection systems and energy flow are to be studied in detail and implemented.

(d) IBR with GFM inverters provide black start services instantaneously:
GFM based IBRs have faster response than synchronous generators. In addition, they can provide voltage and frequency support during black start. Also, they can operate at levels lower than rated capacity for longer time and with stability unlike synchronous generators. These attributes give flexibility to the grid operators during black start sequencing. Also, IBR like battery energy storage systems (BESS) are capable of providing auxiliary power (emergency power or kick start-up power) for starting large synchronous generators. The flexible control and fast response of IBR could assist in stabilising grid frequency during a black start sequence, where the lead black start units are conventional synchronous power plants. The transmission line connected IBRs provide black start services. The IBR that are connected to the grid at distribution voltage level can form islands within their distribution system. It is possible to synchronise these islands among themselves, which will help in restarting the grid. Provision of in-rush current limiting devices such as soft start for large loads will be additional help during black starting[31].

25. Summary Comparison Table

The following table[28] from 'EPRI Tutorial - 2023 - Grid Forming Inverters' summarises a few characteristics for comparison between GFL and GFM inverters.

Subject	GFL Inverter Controls	GFM Inverter Controls
Basic control objectives	Deliver power to an *energised* grid	Set up *grid voltage and frequency*
Requirement of stiff voltage at the point of connection	Always needed as it cannot generate its own voltage reference	Not needed; will generate its own voltage reference
Control circuits	Always needs PLL	Will work without PLL also
Output parameters which are controlled	AC current: (Magnitude and phase)	AC voltage: (Magnitude and frequency)

26. Renewable Energy is set to Grow Rapidly in Future Grids [26,27,28]:

The present GFL inverters face issues mainly when operating in weak grids, as their control circuits are designed and tuned for strong grid operation dominated by large synchronous generators. The PLL controls embedded in GFL designs are used for obtaining synchronisation with the grid. PLL is not the only cause of instability in a weak grid. Inverter control with PLL can be developed to work in weak or even in a grid with only IBR in future, with support from research in this area. Currently, GFM inverters are primarily considered in microgrids and transmission systems with low fault current and rotational inertia. Most of the time, the grid will absorb all the electricity produced by renewables because there is sufficient demand for electricity. During rare events, production from renewables exceeds demand for electricity in a given region and production must be curtailed. This may occur quite often in the future as the proportion of renewables in the grid increases. This calls for ultra-dynamic power trading.

At the same time, as more and more renewables are integrated into the grid, their intermittent nature of production of electricity will cause operational issues like in forecasting and meeting load demands. A growing proportion of renewables on the grid makes weather critically important for forecasting net load. Since weather changes rapidly and unpredictably, high renewables penetration requires grid operators to be adaptive and use dynamic reference tables coupled with advanced weather computers to balance demand and supply. A slow response will potentially lead to unscheduled shutdowns and blackouts[32,33], which will attract huge penalties.

27. Implications for the Grid of the Future

Falling costs of manufacture coupled with encouraging government policies, RE is expected to grow significantly in future. The grid side needs to be prepared for receiving the same, which will require a new thinking in planning and scheduling. The ease of operation in a grid can be done through numerous ways, ultimately leading to the smooth integration of IBR into the grid[32,33]. Energy storage can be provided with IBR to accommodate fluctuations in renewable generation over the course of the day or several days (say during monsoon). Electricity can be stored during times of high production (for solar, during sunny days; for wind, during times of high wind speeds) for later use during periods of high demand, typically in the morning and evening peak periods, given the residential and commercial load demand patterns.

Building more transmission lines to interconnect areas gifted with plentiful renewable resources (eg, very sunny or windy areas) with areas of high demand loads can fully utilise renewable resources. This will also reduce uncertainties in the pattern of generation. For example, building solar plants in deserts that get sunshine most of the year can reduce weather-dependent uncertainty associated with the system's production.

28. Homogenising the Grid

A judicious 'all-weather' combination of different types of renewable sources can greatly reduce the unpredictability. For example, a grid that receives electricity from many types of renewable, such as solar, wind, hydro, geothermal, etc, will have a more stable supply of electricity than a grid that relies exclusively on one type only, for instance, solar power.

Demand-side management can be used strategically to optimise the times when electricity is used to reflect the availability of generation. One method may be implemented through TOD (smart) metering, which will reduce demand during peak hours, thus lessening the burden on the grid, increasing the system load factor[32,33].

29. RE Production and Energy Storage in India

Energy storage is expected to be the panacea for stable operation of a grid dominated by IBR. As per the National Electricity Plan (NEP) 2023 of the Central Electricity Authority (CEA), energy storage capacity requirement is projected to be 82.37 GWh (47.65 GWh from PSP and 34.72 GWh from BESS) in 2026-27. This requirement is further expected to increase to 411.4 GWh (175.18 GWh from PSP and 236.22 GWh from BESS) in 2031-32. The BESS growth is spurred by the government's PLI for advanced cell chemistry[34,35].

Both BESS and pumped storage projects (PSP) are emerging fast as viable energy storage solutions. BESS offers fast response time and can be located or relocated easily as per grid requirements. PSP can support for longer duration and have an excellent life. Its location cannot be moved. But as BESS prices are falling rapidly, more BESS storage may off-set merits of PSP. Still, it is felt that it would be ideal to keep both types of storage systems in hand for any contingency requirement.

Further, CEA has also projected that by 2047, the requirement of energy storage is expected to increase to 2,380 GWh (540 GWh from PSP and 1,840 GWh from BESS) due to the addition of a larger amount of RE in light of the net-zero emission targets set for 2070. Further stimulus is foreseen from the recent mandate, which calls for solar energy tenders to include BESS equivalent to 10 percent of the capacity for two-hour duration[34,35]. India's total electricity generation capacity has reached 452.69 GW, with RE contributing a significant portion of the overall power mix. As of October 2024, RE-based electricity generation capacity stands at 203.18 GW, accounting for more than 46.3 percent of the country's total installed capacity. A variety of RE resources contribute to this capacity, as listed in the table[35] below:

Type of Renewable Power:	Capacity	Unit
Solar power:	92.12	GW
Wind power:	47.72	GW
Hydroelectric power:	46.93	GW
Small hydro power:	6.07	GW
Bio Power (biomass and biogas energy):	11.32	GW

30. Conclusion

RE is the perfect foundation for a low carbon future. Research work is underway to design inverters in IBR to function without failure even in adverse grid conditions without support from synchronous generators. BESS, whose prices are rapidly falling, can give tremendous support to grid stability in an IBR dominated grid.

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ABOUT THE AUTHOR

SV Varadarajan, Retired Technical Director, M. N. Dastur & Company (P) Ltd, Chennai, has nearly 41 years of work experience in consultancy, erection, testing and commissioning and maintenance of electrical, instrumentation and automation works in various integrated iron and steel projects and in thermal power plants in India and abroad. He has served as a member in BIS' Rotating Machinery Sectional Committee (ETD-15). Varadarajan has also delivered a number of lectures for students and faculty members in engineering colleges in the Chennai region. He is a graduate EE from Dr. Alagappa Chettiar College of Engineering and Technology, Karaikudi, Tamil Nadu, and has a PG Diploma in Business Management from AIMA, New Delhi.

Electrical Fire Safety Conclave, Mumbai

To promote safe and reliable practices in electrical installations and usage according to the latest national regulations, IEEMA commenced the first of its series of Electrical Fire Safety Conclaves in Mumbai, with Delhi, Bengaluru Kolkata to follow.

Inaugural Session

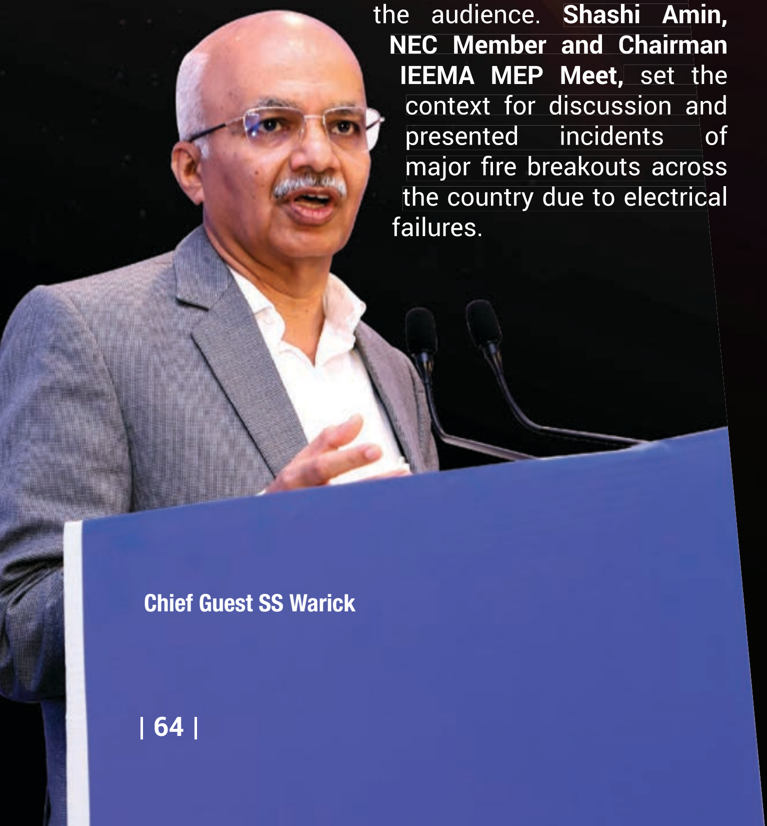
In a first of its series of the Electrical Fire Safety Conclaves across cities in the country, IEEMA commenced its first conclave in Mumbai on April 23, 2025. IEEMA's electrical safety campaign is an effort to promote safe and reliable practices in electrical installations and usage according to the 'Measures Relating to Safety and Electric Supply Regulations 2023' and the 'National Electrical Code of India 2023'. Key takeaways from the sessions included: understanding the importance of electrical safety; understanding the new statutory and mandatory requirements under relevant laws; identifying electrical hazards and how; knowledge of control measures, best practices and technologies; and understanding safety procedures while installing electrical equipment and during maintenance work.

Inaugural Session

The conclave in Mumbai welcomed more than 200 delegates to collaborate on building a safer electrical system. It began with dignitaries lighting

Lighting of lamp

the ceremonial lamp. **Sanjay Kulkarni, Chairman-Western Region, IEEMA,** welcomed the gathering, saying, "The Fire Safety Conclave is not just an event, it is a platform to deliberate on one of the most important topics. IEEMA is hosting this conclave across cities to highlight this topic, where experts can meet, interact, and chalk out a way forward." This was followed by **Dr. Kamal Goliya, Chairman, IEEMA MSME Division and Mihir Merchant, Vice Chairman, IEEMA International Business Division,** addressing the audience. **Shashi Amin, NEC Member and Chairman IEEMA MEP Meet,** set the context for discussion and presented incidents of major fire breakouts across the country due to electrical failures.



Chief Guest SS Warick

Chief Guest Santosh Warick, Director, Maharashtra Fire Services, Government of Maharashtra, threw a backdrop of the fire provisions across the country and congratulated IEEMA for discussing this topic on fire safety. He emphasised the importance of fire safety, especially with Mumbai having more than 28,000 high-rises, and urged stakeholders to take immediate action, starting with simple home precautions. "India has the best standards, including the National Building Code (NBC), in place for fire and safety as well. While these standards are in place, implementing challenges exist. When we talk about developed *Bharat*, we must have a *surakshit Bharat* as well." He also called for recommendations on the NBC, which is currently under revision.

Session 1: Regulatory Framework: Provisions, Challenges and Opportunities

The first session titled 'Regulatory Framework: Provisions, Challenges and Opportunities' was moderated by **Rupesh Gujarathi, Founder & Director, Electro-Mech Consultants.** Panellists included **Vikram Thorat, IES, Assistant Director, CEA, Mumbai; Rajendra Sethiya, Business Unit Head-City Zone, Tata Power Co Ltd; Ashweni Jain, Head-Diagnostic Cell, Adani Electricity Mumbai Ltd; Abhijeet V Limaaye, Senior Consultant, VLE Engineers Pvt Ltd; and Bhagwat K. Ugale, Electrical Inspector-Nashik, Industries, Energy, Labour and Mining Department, Government of Maharashtra.** Experts from leading companies came together to discuss existing

Session 1: Regulatory Framework: Provisions, Challenges and Opportunities

Case Study by Sheetal Bhilkar

fire safety regulations, implementation gaps, and opportunities for strengthening the compliance ecosystem.

Case Study

Sheetal Bhilkar, Founder-Director, Urja Building Services Consultants Pvt Ltd, presented an interesting case study on 'Fast Track & Innovative Electrical Safety Solutions'.

Session 2: Electrical Fire Safety in Today's Buildings & Construction

In Session 2, moderated by **Vinayak Sane, Managing Director, "Abhiyanta" Consulting Engineers LLP,** panellists discussed the evolving

Session 2: Electrical Fire Safety in Today's Buildings & Construction

Session 3: Electrical Fire Safety in IT Parks and Data Centres

landscape of electrical fire safety in building and construction. Panellists of this session included **Dr. Niranjan Khambete, Hospital Safety, Deenanath, Mangeshkar Hospital, Pune; Trinadh Kothapalli, Scientist 'D', Jt. Director, BIS; Ajit Ramdas Garve, National Leader-Strategic Accounts – Building Automation, Honeywell India; Arvind Mandke, Former CFO, TMC & CIDCO & Fire Advisor, JNPA; and Debajyoti Mukherjee, Vice President, Polycab India Ltd.**

Session 3: Electrical Fire Safety in IT Parks and Data Centres

The third session titled 'Electrical Fire Safety in IT Parks and Data Centres' was led by **NK Jain, Director, N K Jain Consulting Engineer,** with panellists **Akash Ajmera, CEO and Co-Founder, ADN Fire Safety Pvt Ltd; Rajen Mehta, CEO, Efficienergi Consulting Pvt Ltd;** and **Jeyabalan Kuthalingam, Engineering Head, Princeton.** The discussion addressed the growing need for robust safety protocols in digitally intensive environments.

Case Study by Shahzeb Lehry

Case Study

Shahzed Lehry, Officer (HQ), Additional Controller of Civil Defence, Home Department, Government of Maharashtra, presented simple but important tips on how fire incidents can be avoided and safety can be prioritised.

Session 4: Best Practices and Technologies of Electrical Fire Safety

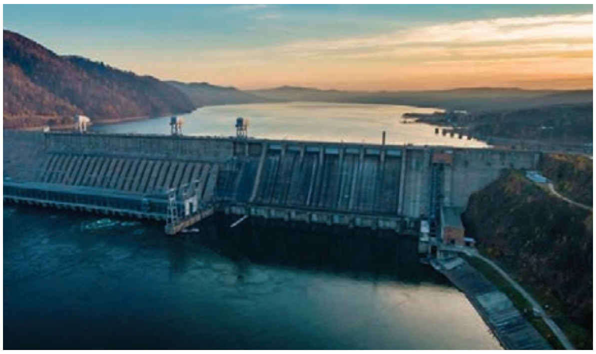
The concluding session focussed on 'Best Practices and Technologies of Electrical Fire Safety' moderated by **Narendra Duvedi, Mentor, Sas Powertech Pvt Ltd.** Panellists included **Mohd Haroon Siddiqui, Sr. Vice President Corporate Head MEP, Rustomjee; Santhosh Jayarajan, General Manager-MEP, TATA Realty & Infrastructure Ltd; Ajit Kulkarni, Director, Ajit Kulkarni Consultants Pvt Ltd; Chidambar Joshi, Director, Maitriser Technologies Pvt Ltd; Bhushan Mankame, Electrical Engineer, National Federation of Engineers for Electrical Safety (NFE);** and **Deepak Tikle, Executive Director, V-Marc India Limited.** The esteemed panellists from diverse industries shared their perspectives and solutions for enhanced safety standards.

The power-packed conclave concluded with a summary, key takeaway points, and vote of thanks by **Rakesh Telawne, Vice Chairman, IEEMA Western Region.** The first of the series of the Fire Safety Conclave set a robust platform for discussing this important topic to make an electrical safe India.

Stay tuned for the upcoming Fire Safety Conclaves: Delhi on May 16, Bengaluru on June 6, and Kolkata on July 11.

Session 4: Best Practices and Technologies of Electrical Fire Safety

CEA plans to concur minimum 13 pumped storage projects of 22 GW for 2025-26



The Central Electricity Authority (CEA), under the Ministry of Power, Government of India, has concurred detailed project reports (DPRs) of six hydro pumped storage projects (PSPs) of about 7.5 GW in record time during 2024-25, marking a key milestone in India's ongoing commitment to developing advanced long term energy storage solutions. These six PSPs are: Upper Indravati (600 MW) in Odisha, Sharavathy (2,000 MW) in Karnataka, Bhivpuri (1,000 MW) in Maharashtra, Bhavali (1,500 MW) in Maharashtra, MP-30 (1,920 MW) in Madhya Pradesh, and Chitravathi (500 MW) in Andhra Pradesh.

CEA has made ambitious plan to concur minimum 13 PSPs of about 22 GW during 2025-26. The target is to commission most of these PSPs in four years and latest by 2030. Development of these projects shall boost energy storage capacity drastically in the country, making a major contribution to grid reliability and supporting India's ambitious renewable energy goals. This further underscores the CEA's ongoing commitment for facilitating the transition towards a more sustainable and resilient power system.

The participation of private sector in this segment is quite encouraging and with the help of self-identified PSP, the PSP potential in the country has crossed 200 GW, further increasing almost every month. From a meagre 3.5 GW of operational hydro PSP capacity in the country, the development needs to be taken up in an accelerated mission mode to harness this potential.

This year, two PSPs of about 3,000 MW will be commissioned and by 2032, about 50 GW is expected. At present, eight projects of 10 GW are under construction and DPRs have been concurred for three projects of about 3 GW. In addition to this, 49 projects of 66 GW are under survey and investigation. All these DPRs are expected to be finalised by the developers in two years.

Hydro PSPs are vital for energy transition as they allow excess electricity generated during off-peak hours to be stored in the form of water in elevated reservoirs. This stored energy can then be used back during non-solar hours peak demand periods, ensuring a reliable, consistent, and flexible power supply.

For developers and investors, it is a great investment opportunity to develop and invest in long-term assets of more than 70-80 years.

Union Commerce & Industry Minister Shri Piyush Goyal calls for investments in emerging technologies to propel 'Viksit Bharat 2047' Vision

Union Minister of Commerce & Industry, Shri Piyush Goyal, at a recent event, highlighted the need for investments in emerging technologies such as robotics, automation, machine learning (ML), 3D manufacturing, and next-generation factories. He reportedly said, these innovations are essential for realising the vision of 'Viksit Bharat 2047' and establishing India as a global leader in industry and innovation.

Shri Goyal also underscored the evolving role of startups in driving India's economic and technological growth and encouraged Indian investors to support the domestic startup ecosystem. He also stressed the need for increasing domestic capital investments, stating that a strong foundation of indigenous investment is crucial to reducing dependency on foreign capital and ensuring long-term economic resilience.

Shri Goyal emphasised the need to attract more domestic investors to strengthen India's capital base and ensure self-reliance. As reported, he urged domestic investors to invest in the country's startups.

Highlighting India's economic trajectory, Shri Goyal noted that India is on track to become the fourth largest by the end of 2025 and the third largest by 2027, surpassing Japan and Germany. He credited this growth to India's robust startup ecosystem, rapid advancements in artificial intelligence, semiconductor manufacturing, and deep-tech innovations.

MNRE notifies guidelines for prototype wind turbine testing

The Ministry of New and Renewable Energy (MNRE) has reportedly issued revised guidelines for installation of prototype wind turbine models. The revised guidelines allow prototype wind turbines a maximum of three years to complete

type testing and obtain certification from internationally accredited agencies. The guidelines form part of an updated framework for prototype wind turbine installations, to be implemented by the National Institute of Wind Energy (NIWE), Chennai.

As per the draft, prototype models will reportedly be installed solely for the purpose of type testing. As reported, a recommendation letter from NIWE will be issued to initiate testing, with a maximum three years to be allowed to obtain the type certificate. The prototype certificate will remain valid during this period. In case of revisions to an existing prototype, a new recommendation letter is required to be obtained, and testing is to be completed within the validity of the updated certificate. The prototype certificate will have a maximum validity of three years, with possible extensions.

The draft also mandates regular operation and maintenance (O&M) of prototype turbines. Certification agencies are required to issue annual reports confirming O&M compliance; failure to this may result in disconnection from the grid. All prototype wind turbines are required to be commissioned within 18 months of receiving the NIWE recommendation letter.

MHI achieves sales of more than 1 million EVs in FY2024-25

India's e-mobility sector is gaining momentum, driven by government initiatives, technological advancements, and environmental concerns. The growth story of electric mobility is visible by the numbers below:

In FY2024-25, a total of 1,149,334 electric two-wheelers (e-2W) were sold, reflecting a 21 percent increase compared to 948,561 units sold in FY2023-24. Similarly, the sales of electric three-wheelers e-3W (L5) reached 159,235 units in FY2024-25,

marking a 57 percent growth over the 101,581 units sold in the previous financial year.

The Ministry of Heavy Industries (MHI) has notified the 'PM Electric Drive Revolution in Innovative Vehicle Enhancement (PM E-DRIVE) Scheme' on September 29, 2024, to provide impetus to the green mobility and development of electric vehicle (EV) manufacturing eco-system in the country. The scheme has an outlay of Rs10,900 crore over two years up to March 31, 2026. The Electric Mobility Promotion Scheme (EMPS) 2024 implemented by MHI for six months – from April 01, 2024, to September 30, 2024, is subsumed in the PM E-DRIVE scheme.

Under the PM E-DRIVE scheme, in FY2024-25, 1,010,101 e-2W and 122,982 e-3W(L5) have been registered in the VAHAN portal. Sales of more than 1 million EVs is witnessed in FY2024-25.

Union Minister for Heavy Industries & Steel, Shri HD Kumaraswamy, lauded this achievement and stated:

The PM E-DRIVE Scheme, spearheaded by MHI, has played a pivotal role in accelerating electric vehicle adoption by offering financial incentives, promoting indigenous manufacturing, and strengthening the EV ecosystem. The scheme's impact data up to March 31, 2025, is reflected in the following key environmental benefits: Fuel saving per day – 855,723 litres; total fuel saved – 1,577,33,334 litres; CO_2 reduction per day – 1,248,100 kg; total CO_2 reduction – 2,301,73,978 kg.

Through the promotion of EVs and supporting infrastructure, the scheme is expected to catalyse significant investments in the EV sector and its supply chain. Furthermore, it will generate substantial employment opportunities across the value chain, including jobs in manufacturing and charging infrastructure setup. Overall, this scheme represents a crucial step toward a cleaner, more sustainable future for transportation in India.

The Production Linked Incentive (PLI) Auto Scheme is transforming India's automotive sector by driving sustainable and advanced manufacturing. Under this initiative, 18 original equipment manufacturers (OEMs) have applied, playing a crucial role in accelerating the electric mobility revolution and strengthening the nation's journey towards a self-reliant and future-ready automotive ecosystem.

Shri Pralhad Joshi inaugurates a 5.4 GW high-tech plant at Chikhli in Gujarat

Union Minister of New and Renewable Energy Shri Pralhad Joshi inaugurated a state-of-the-art 5.4 GW solar cell gigafactory/manufacturing facility of Warree Energy at Chikhali in Gujarat.

As India's largest state-of-the-art solar cell production plant, this landmark achievement is a decisive step towards strengthening the domestic solar supply chain and reducing dependence on imports, while the global solar energy value chain is also at the forefront of the country's march as a net exporter and enabler in the ecosystem.

Speaking on the occasion, a PIB release quoted Minister for New and Renewable Energy, Shri Pralhad Joshi saying, "This magnificent facility embodies the spirit of India and stands in the form of India's growing expertise in the global renewable energy scenario. This is in full alignment with our national vision of establishing India as a global manufacturing hub for clean energy technologies. The plant will not only cater to local needs but also position India as a major exporter of advanced solar technologies."

Shri Pralhad Joshi went on to say that India is not only participating in the global energy revolution but is leading it. "Today, we have become the third largest renewable energy capacity in the world. In the last 10 years, there has been an extraordinary increase in the solar power capacity in the country – from 2.82 GW in 2014 to 104 GW, showing a significant increase of 3580 percent," he said, as per the release.

He concluded saying, "We are proud that this plant with its full potential will contribute to making India a global powerhouse in solar energy."

NATIONAL

IndiGrid commissions India's first regulated utility-scale standalone BESS project

IndiGrid has commissioned what is reportedly India's first regulated utility-scale standalone battery energy storage system (BESS) project – Kilokari BESS Private Limited – with a capacity of 20 MW/40 MWh in Delhi. Representing IndiGrid's first commercial BESS initiative, the project aims at supporting renewable energy integration into the distribution-level grid system. The system also aims at facilitating grid stabilisation, managing peak electricity demand, and addressing ancillary requirements.

CIL-DVC sign MoU for 2 x 800 MW thermal power plant in Jharkhand

Coal India Limited (CIL) has signed an MoU with Damodar Valley Corporation (DVC) to jointly develop a coal-fired 2 x 800 MW ultra supercritical power plant in Jharkhand. As reported, this brownfield project will be an expansion of the existing Chandrapura thermal power station with a current capacity of 2 x 250 MW. The project is proposed at a total investment of Rs165 billion. The joint venture company will have a 50:50 equity sharing model.

PFCCL incorporates three SPVs for development of transmission projects

PFC Consulting Limited (PFCCL) has incorporated three special purpose vehicles (SPVs) – Mandsaur I RE Transmission Limited, Vindhyachal Varanasi Transmission Limited, and Morena I SEZ Transmission Limited – as wholly owned subsidiaries for developing transmission schemes. Mandsaur I RE Transmission Limited is established for augmenting transformation capacity and implementing line bays at Mandsaur substations for renewable energy interconnection. Vindhyachal Varanasi Transmission Limited will develop an inter-regional (NR-WR) transmission system to relieve the loading of the 765 kV Vindhyachal-Varanasi double circuit line. Morena I SEZ Transmission Limited will develop the transmission system for evacuating 2,500 MW of power from renewable energy projects in Morena SEZ, Madhya Pradesh (Phase I).

Prime Minister lays foundation stone for energy projects in Haryana

The Prime Minister has inaugurated construction of the 800-MW Deen Bandhu Chhotu Ram Power expansion project in Yamuna Nagar, Haryana. Haryana Power Generation Corporation Limited will develop the project – comprising the expansion of the existing 2 x 300 MW power plant commissioned in 2008 – at an estimated Rs 84.7 billion. The Prime Minister has also announced a target to raise Haryana's total power generation capacity from the current 16,000 MW to 24,000 MW.

NHPC commences operations for 107.14 MW unit of Karnisar solar project in Rajasthan

NHPC Limited has commenced operations for the 107.14-MW unit of the Karnisar solar power project in Bikaner, Rajasthan, in April 2025. This forms part of the company's 300 MW solar project at site. The project is connected to the interstate transmission system (ISTS), with initial injection of 31 MW starting in March 2025. The commercial operations date (COD) for the balance capacity will reportedly be announced in phases, with full commissioning expected by August 31, 2025.

SECI and KSEB sign agreement for 125 MW/500 MWh BESS project in Kerala

Solar Energy Corporation of India Limited (SECI) has entered into a battery energy storage sale agreement with Kerala State Electricity Board (KSEB) for a grid-connected standalone battery energy storage system (BESS) project of 125 MW/500 MWh capacity. The project will be developed, operated, and maintained by JSW Energy, which secured the project through a competitive auction conducted by SECI at a tariff of Rs441,000 per MW per month. The BESS is intended to be available for KSEB to charge and discharge on an on-demand basis, enabling the state utility to manage its grid requirements efficiently. The project, as reported, is also eligible for viability gap funding.

NGEL commissions 90 MW unit of Dayapar wind project in Gujarat

NTPC Green Energy Limited (NGEL) has commissioned a 90-MW unit of the Dayapar wind energy project phase-I in Gujarat. This marks the second part of the total 150-MW capacity planned for Phase-I, which falls under the larger 450-MW hybrid renewable energy project being developed at Bhuj.

BPCL and Sembcorp form JV to develop clean energy projects in India

Bharat Petroleum Corporation Limited (BPCL) and Sembcorp Green Hydrogen India Private Limited, a wholly owned subsidiary of Sembcorp Industries Limited, have signed a joint venture (JV) agreement to develop renewable energy and green hydrogen projects across the country. As reported, the JV will also assess opportunities in green ammonia production, bunkering, emissions reduction for port operations, and other emerging technologies in green fuels.

BHEL and Hitachi Energy secure HVDC terminal contract for Bhadla-Fatehpur project

Bharat Heavy Electricals Limited (BHEL) and Hitachi Energy India Limited have secured a contract from Rajasthan Part I Power Transmission Limited, a wholly owned subsidiary of Adani Energy Solutions Limited, for designing and executing the ±800 kV, 6000 MW line commutated converter high voltage direct current (HVDC) terminals at Bhadla and Fatehpur. The scope of work includes design, supply, installation, and commissioning of bi-directional HVDC terminals to transmit renewable energy over 950 km from Bhadla in Rajasthan to Fatehpur in Uttar Pradesh. BHEL will reportedly supply key equipment such as converter transformers, shunt reactors, filter bank capacitors and instrument transformers from its Bhopal plant, along with thyristor valves from its Bengaluru unit. The project also includes a 765 kV/400 kV power evacuation system at Fatehpur terminal and a 400 kV substation at Bhadla and its extension.

SJVN Green Energy commissions 241.77 MW solar project in Rajasthan

SJVN Green Energy Limited has commenced operations for a 241.77-MW of the company's 1,000 MW solar power project in Bikaner, Rajasthan. The project is being developed in phases, with the total planned capacity of 1,000 MW expected to be fully operational by September 30, 2025. On completion, the solar power generated from this project will be supplied to Rajasthan, Jammu & Kashmir, and Uttarakhand.

BHEL receives LoI for EPC package for 1,320 MW Korba West thermal power plant in Chhattisgarh

BHEL has received a letter of intent (LoI) for engineering, procurement, and construction (EPC) for the 1,320-MW Rajiv Gandhi (Korba West) thermal power plant. The scope of work includes supply of supercritical equipment, boiler, turbine, generator and associated auxiliaries along with electrical, control and instrumentation, balance of plant packages, erection and commissioning.

NHPC connects 300 MW Bikaner solar PV project with ISTS

NHPC Limited has, as reported, successfully connected its 300-MW Bikaner solar photo voltaic (PV) project with inter-state transmission system (ISTS) and started injecting 31 MW power in the grid as on March 31, 2025. The commercial declaration of part capacity of 100 MW in phases is expected to be intimated in due course. The complete 300 MW solar project will reportedly be commissioned by August 2025.

PFCCL incorporates NES Pune East New Transmission

PFC Consulting Limited (PFCCL) has incorporated an SPV – NES Pune East New Transmission Limited – for developing the 'Network Expansion scheme in Maharashtra for removal of Transmission Constrains in Pune Region-I (765/400 kV Pune East)'. The Maharashtra State Electricity Transmission Company Limited has appointed PFCCL as the bid process coordinator for selecting the bidder as transmission service provider to establish the transmission system through tariff-based competitive bidding process.

NTPC commissions 245 MW solar project at Nokh, Rajasthan

NTPC Limited has commissioned commercial operations of a 245-MW solar power project at Nokh, Rajasthan, following successful commissioning and regulatory clearances. This is part of its 3 x 245 MW Nokh solar PV project. NTPC's total installed and commercial capacity on a standalone and group basis now stands at 59,413 MW and 77,806.50 MW, respectively.

INTERNATIONAL

India and Sri Lanka sign MoU for solar projects and HVDC interconnections

India and Sri Lanka have signed a memorandum of understanding (MoU) to jointly develop a 120-MW solar power project in Sampur in the Trincomalee district of Sri Lanka. Furthermore, an MoU has also been signed for implementing an HVDC interconnection between India and Sri Lanka for facilitating import-export of power. This apart, an MoU has also been signed for supplying and installing rooftop solar systems at 500 religious institutions across Sri Lanka.

MAHAGENCO and Russia's Rosatom sign cooperation agreement for thorium-based SMR development in Maharashtra

Maharashtra State Power Generation Corporation Limited (MAHAGENCO) has signed a cooperation agreement with Russia's state-owned Rosatom for the joint development of a small modular reactor (SMR) using thorium fuel. As part of the agreement, both parties will reportedly collaborate for development and commercialisation of a thorium reactor as per the atomic energy regulatory board (AERB) safety standards. It also includes the establishment of an assembly line under the 'Make in Maharashtra' initiative.

Bajel Projects commissions 132 kV transmission line for ZESCO in Zambia

Bajel Projects Limited, a Bajaj Group company, has successfully commissioned a 132-kV single circuit transmission line project for Zambia Electricity Supply Corporation Limited (ZESCO) in Lusaka, Zambia. The project comprises three key transmission lines: Coventry-Waterworks (3.5 km), Jimmy-Chawama (7.5 km), and Coventry-Jimmy (2.5 km), designed to enhance grid reliability and support Lusaka's growing power demand.

HFE signs MoU for green hydrogen project in Vietnam

Hero Future Energies Private Limited (HFE) has signed an MoU with the Binh Dinh Provincial Department of Finance in Vietnam. This MoU pertains to the development of a proposed US$ 200-million green hydrogen production project in the Binh Dinh province.

CORPORATE

BC Jindal Group to invest Rs150 billion in RE components manufacturing

BC Jindal Group is foraying into the renewable energy component manufacturing sector with a planned investment of Rs150 billion by 2030. The group reportedly aims at establishing production capacities across the solar and battery storage segments. In the first phase – which will include setting up 2 GW solar cell and module manufacturing capacity, a 4 GWh battery storage facility, and a solar glass production unit with a capacity of 1,200 tonne per day – the group will invest Rs40 billion. Maharashtra and Gujarat have been shortlisted as potential locations for establishing these facilities.

Tata Power to install 100 MW BESS in Mumbai

Tata Power will reportedly install a 100-MW battery energy storage system (BESS) across 10 strategic locations in Mumbai in two years, following approval from the Maharashtra Electricity Regulatory Commission. The company aims at ensuring uninterrupted power supply to critical infrastructure such as metros, hospitals, airport, and data centres during grid disturbances, while also supporting grid stability through islanding to prevent blackouts. As reported, the BESS will be equipped with advanced 'black start' functionality for rapid power recovery and will help manage peak load efficiently. The system will also provide ancillary services such as frequency regulation and voltage support, and enable better utilisation of renewable energy, particularly solar power.

L&T forms new subsidiary to develop green hydrogen projects

Larsen & Toubro (L&T) has incorporated a new subsidiary – L&T Green Energy Kandla Private Limited – through its wholly-owned unit L&T Energy Green Tech Limited. The new arm has been specifically formed for developing green hydrogen and its derivatives, including green ammonia, along with undertaking related business activities.

ReNew commissions 1.3 GWp solar project in Rajasthan

ReNew has commissioned a 1,300-MW peak solar power project spread over approximately 3,500 acre in Jaisalmer, Rajasthan. As reported, about 90 percent of the solar panels used in this utility-scale installation have been manufactured at ReNew's

Jaipur factory. The project is expected to reportedly meet the annual energy needs of about 500,000 households in Rajasthan.

TPREL signs PPA with NTPC for 200 MW firm RE project

Tata Power Renewable Energy Limited (TPREL), a wholly owned subsidiary of Tata Power Limited, has signed a power purchase agreement (PPA) with NTPC Limited for supplying 200 MW of firm and dispatchable renewable energy. The project includes provisions for assured power supply based on the buying entity's scheduling needs. The PPA is valid for 24 months and includes a capital commitment of approximately Rs45 billion.

JSW Neo acquires 4.7 GW RE platform from 02 Power

JSW Neo Energy Limited, a wholly owned subsidiary of JSW Energy Limited, has acquired a 4.7-GW RE platform from 02 Power Pooling Pte Limited, a joint venture between global investors EQT and Temasek, for Rs 124.68 billion, including operational and under-construction assets. Of the total capacity, 2,259 MW is expected to become operational by June 2025, generating steady-state EBITDA of Rs15 billion. JSW Neo plans to reportedly invest an additional Rs135 billion to reach its full capacity of 4,696 MW by June 2027.

Evren and NTPC signs PPA for 300 MW FDRE

Evren has signed a power purchase agreement (PPA) with NTPC Limited to supply 300 MW of firm and dispatchable renewable energy (FDRE). Evren will reportedly develop nearly 1 GW of capacity comprising solar, wind, and BESS. As reported, the project is designed to enable efficient peak-hour energy dispatch and help power distribution companies meet renewable energy consumption and energy storage obligations.

JSL Super Steel signs PPA with Sunsure Energy for 11 MWp solar power

JSL Super Steel, a subsidiary of Jindal Stainless Limited, has signed a long-term PPA with Sunsure Energy to procure 11 MWp of solar power for its Ghaziabad facility in Uttar Pradesh. The agreement is part of Sunsure's 49 MWp solar project located in Augasi, Uttar Pradesh, and will be executed under the state's Power Banking Policy. The 11 MWp solar supply is expected to meet nearly 40 per cent of the Ghaziabad plant's conventional energy demand, enabling the facility to transition significantly toward clean energy usage.

Kosol Energie secures 400 MW solar module supply order for NTPC's Khavda project

Kosol Energie Private Limited has secured a 400-MW PV module supply order for NTPC Limited's 1,600 MW Khavda solar project in Gujarat. The company is supplying 550W mono PERC glass-to-backsheet bifacial modules for the project. These modules have reportedly been approved by NTPC following vendor and quality evaluation, after which Kosol Energie was designated as a category-1 prime supplier for the project. As reported, the modules have been specifically designed to endure the harsh climatic and environmental conditions in the Khavda region, ensuring long-term reliability and performance.

Waaree Renewable Technologies lists on NSE

Waaree Renewable Technologies Limited has been officially listed on the National Stock Exchange of India (NSE). The NSE listing is expected to enhance Waaree's market visibility, investor engagement, and access to capital for future expansion. The company aims at scaling up its solar capacity, pursuing hybrid energy opportunities, and growing its presence in domestic and international markets.

Inox Solar secures land in Odisha for 4.8 GW solar manufacturing plant

Inox Solar, a wholly owned subsidiary of Inox Clean and part of the INOXGFL Group, has received land allocation from the Odisha government for setting up a 4.8 GW solar cell and 4.8 GW solar module manufacturing plant in Dhenkanal at Rs40 billion. The allocated land spans approximately 78 acre and will house a state-of-the-art manufacturing facility.

Kundan Green Energy acquires 11.5 MW waste-to-energy plant in Jabalpur

Kundan Green Energy has acquired an 11.5-MW operational waste-to-energy plant from Jabalpur MSW Private Limited through proceedings under the insolvency and bankruptcy code initiated by the State Bank of India. It processes approximately 450 tonne of municipal solid waste per day, with power generated being supplied to the Madhya Pradesh Electricity Regulatory commission's grid.

HFE signs PPA with SJVN for 120 MW renewable-plus-storage project

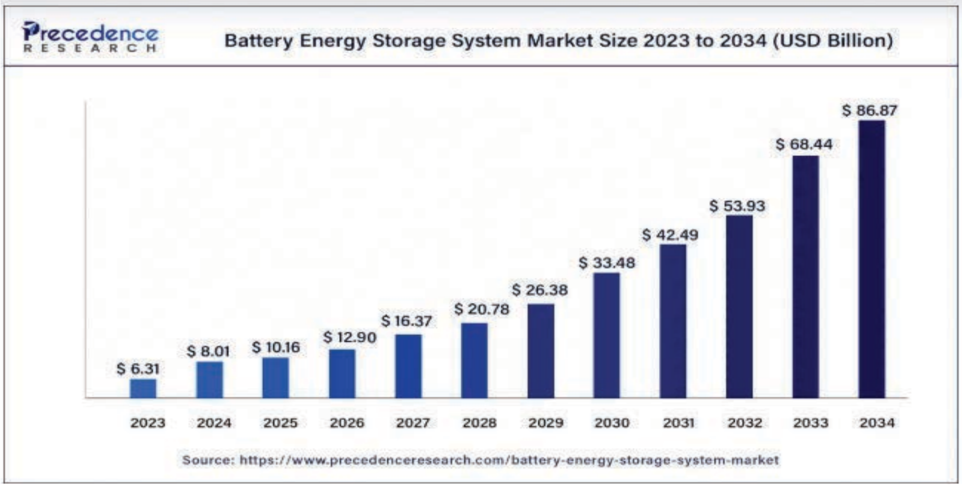
Hero Future Energies Private Limited (HFE) has signed a PPA with SJVN Limited to supply 120 MW of firm and dispatchable power through an RE project integrated with energy storage. The agreement follows the company's successful bid in SJVN's 1,200 MW auction to supply firm and dispatchable power, with HFE securing 120 MW at a tariff of Rs4.25 per kWh. The project, to be developed on a build-own-operate basis, can be established anywhere in India but should be connected to the interstate transmission system. Once operational, the project will reportedly cater to the electricity needs of a prominent state in North India for the next 25 years.

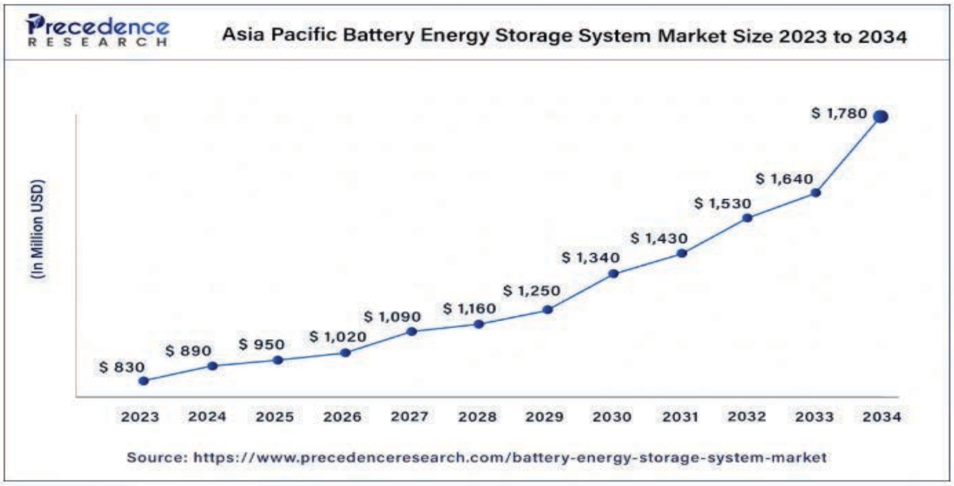
AGEL operationalises additional 480 MW renewable projects at Khavda

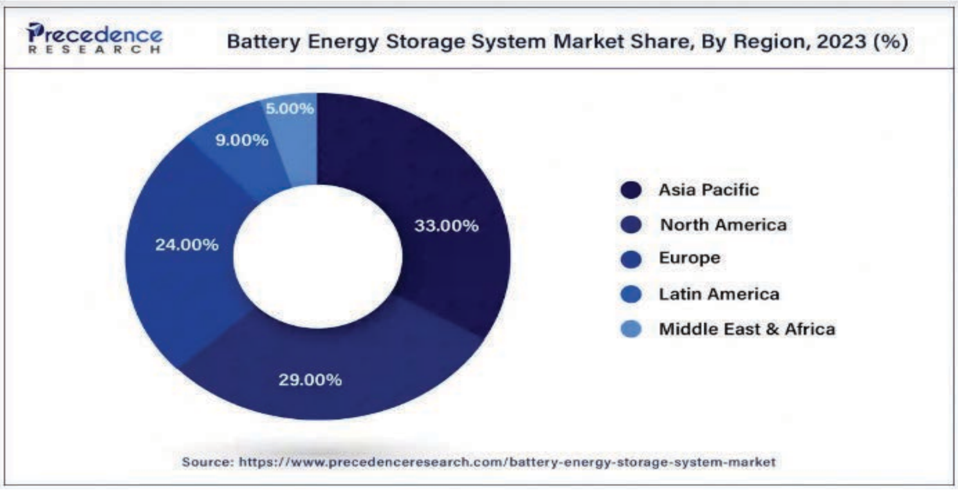
Adani Green Energy Limited (AGEL), through its wholly-owned stepdown subsidiaries – Adani Renewable Energy Fifty Six Limited (solar-125 MW), Adani Renewable Energy Forty One Limited (wind-65.6MW), Adani Renewable Energy Fifty Seven Limited (solar- 37.5MW), Adani Green Energy Twenty Four Limited (wind- 52MW), and Adani Green Energy Twenty Four A Limited (solar- 200MW) – has operationalised an aggregate of 480.1 MW power projects at Khavda, Gujarat. With this, AGEL's total operational renewable generation capacity has increased to 14,217.9 MW.

Global Scenario

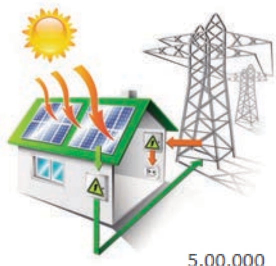
Battery Energy Storage Market





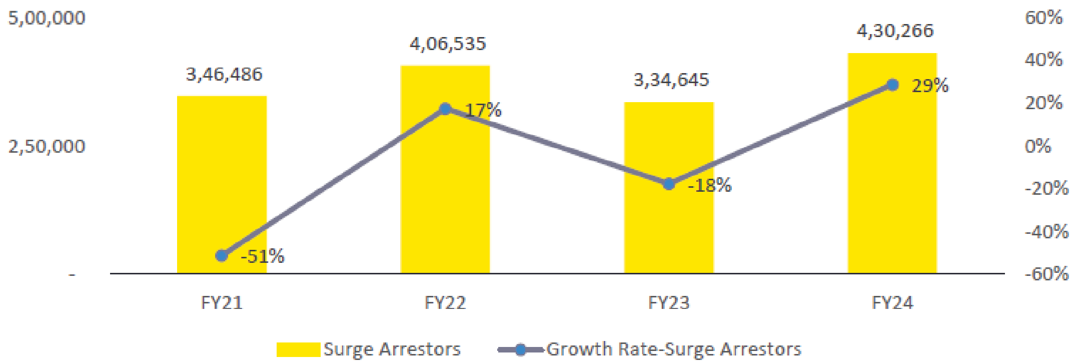


Source: Precedence Research

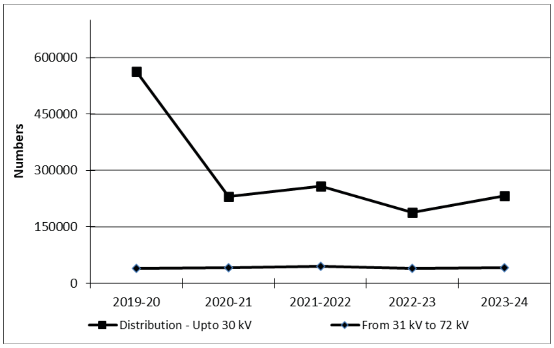


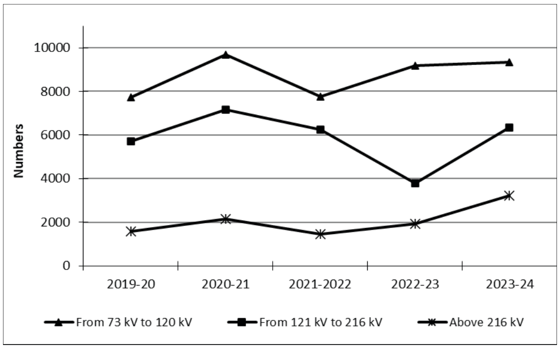
Indian Scenario

Surge Arresers Sales and growth - IEEMA



Sales data trend of Surge Arresters for past Five Years





Consolidated Energy Storage Roadmap

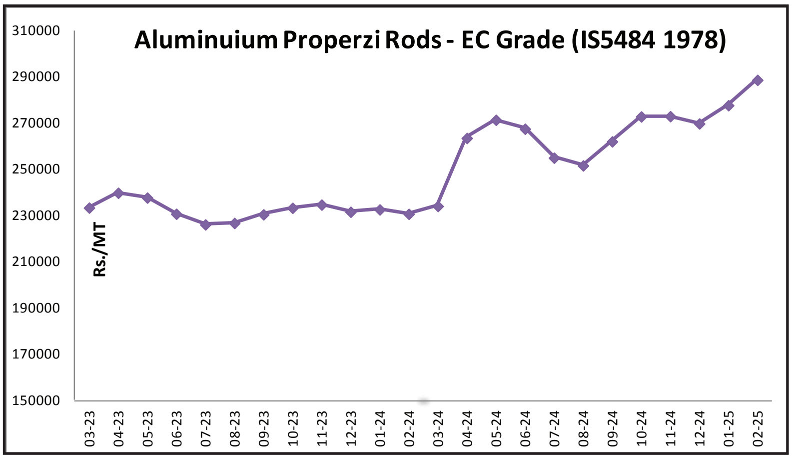
Consolidated Energy Storage Roadmap						
	Applications		Energy Storage (GWh)			
			2019-2022	2022-2027	2027-2032	Total by 2032
Stationary Storage	Grid Support	MV/LV	10	24	33	67
		EHV	7	38	97	142
	Telecom Towers		25	51	78	154
	Data Centres, UPS and Inverters		80	160	234	474
	Miscellaneous Applications (Railways, Rural Electrification, HVAC application)		16	45	90	151
	DG Usage Minimization		-	4	11	14
	Total Stationary (GWh)		138	322	543	1,002
Electric Vehicles	E2W		4	51	441	496
	E3W		26	43	67	136
	E4W		8	102	615	725
	Electric Bus		2	11	44	57
	Total Electric Vehicles (GWh)		40	207	1,167	1,414
Total Energy Storage Demand (GWh)			178	529	1710	2416

Source: IEEMA, ISGF

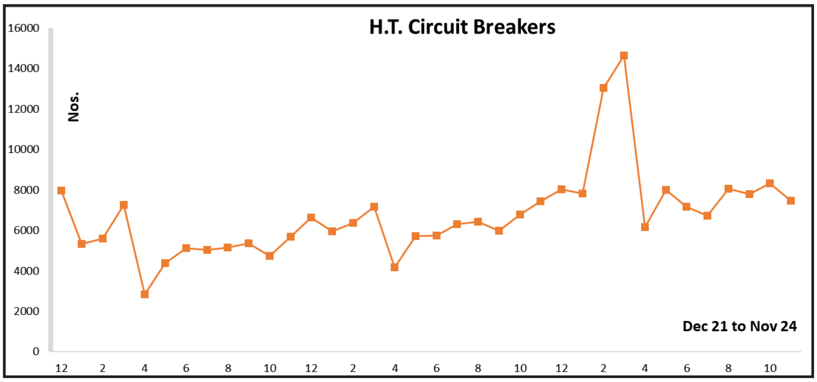
Basic Prices and Indices

	as on February 1, 2025
IRON, STEEL & STEEL PRODUCTS	
BLOOMS (SBLR) 150mmX150mm	43758.00
BILLETS (SBIR) 100MM	46855.00
CRNGO Electrical Steel Sheets M-45,C-6 (Ex-Rsp)	112.23
CRGO Electrical Steel Lamination	665005.00
NON-FERROUS METALS	
Electrolytic High Grade Zinc	283600.00
Lead (99.97%)	200100.00
Copper Wire Bars	860911.00
Copper Wire Rods	879199.00
Aluminium Ingots - EC Grade (IS 4026-1987)	282979.00
Aluminiuium Properzi Rods - EC Grade (IS5484 1978)	288729.00
Aluminium Busbar (IS 5082 1998)	340000.00
OTHER RAW MATERIALS	
Epoxy Resin CT - 5900	766.00

Phenolic Moulding Powder	112.00
PVC Compound - Grade CW- 22	158825.00
PVC Compound Grade HR - 11	159825.00
Transformer Oil Base Stock (TOBS)	96233.00
OTHER IEEMA INDEX NUMBERS	
IN-BUSDUCTS (BASE August 2000=100) FOR THE MONTH December 2024	376.13
IN - WT (BASE JUNE 2000=100)	391.17
Wholesale price index number for 'Insulators' (Base 2011-12 = 100) for the month December 2024	130.50
Wholesale price index number for 'Manufacture of Basic Metals (Base 2011-12 = 100) for the month December 2024	137.50
Wholesale price index number for' Fuel & Power (Base 2011-12 = 100) for the month December 2024	151.80
ALL INDIA AVERAGE CONSUMER PRICE INDEX NUMBER FOR INDUSTRIAL WORKERS (BASE 2016=100) December 2024	143.70
# Estimated, NA: Not available	



Production Statistics



Name of Product	ACC Unit	Production		Highest Annual Production
		For the Month November-24	From Dec 23 to November 24	
Electric Motors				
AC Motors - LT	000' KW	1,532.00	19,861.00	19,195.00
AC Motors - HT	000' KW	388.00	4,988.00	5,273.00
DC Motors	000' KW	33.00	461.00	618.00
Switchgears *				
Contactors	000' Nos.	1,475.00	18,047.00	16,503.00
Motor Starters	000' Nos.	160.00	2,576.00	2,427.00
SDF	000' Nos.	53.00	656.00	752.00
Circuit Breakers DIN Rail Mounted	000' Poles	18,550.00	235,722.00	221,179.00
Circuit Breakers - LT	Nos.	560,852.00	6,250,706.00	5,703,052.00
Circuit Breakers - HT	Nos.	7,454.00	110,314.00	119,282.00
Custom Built Product	Rs. Lakhs	19,356.00	311,473.00	452,536.00
HRC Fuses & Overload Relays	000' Nos.	1,181.00	15,859.00	17,246.00
Power Cables *	KM	79,432.00	1,123,685.00	1,052,205.00
Power Capacitors - LT & HT	000' KVAR	4,902.00	64,896.00	65,385.00
Transformers *				
Distribution Transformers	000' KVA	4,097.00	57,487.00	58,341.00
Power Transformers	000' KVA	21,708.00	235,180.00	234,922.00
Instrument Transformers				
Current Transformers	000' Nos.	850.00	4,553.00	1,390.00
Voltage Transformers	Nos.	17,168.00	208,789.00	217,752.00
Energy Meters	000' Nos.	2,761.00	32,048.00	28,579.00
Transmission Line Towers *	000' MT	93.00	1,125.00	1,250.00

Weighted Production

Source: IEEMA

SHOCKS and SPARKS

FAMOUS FEASTS

During the 1846 election campaign for Congress, Abraham Lincoln, one of the most famous Presidents of America, attended a preaching service of the famous evangelist Peter Cortwright. The evangelist called upon all who wished to go to heaven to stand up. All rose but Lincoln. Again, he called for all to rise who did not want to go to hell. Lincoln kept sitting.

"I am grieved," said Cortwright, "to see Abraham Lincoln kept sitting unmoved by these appeals. If he doesn't want to go to heaven and doesn't want to go to hell, will he tell us where he is going?

Lincoln got up slowly and said, "I am going to the Congress."

Abraham Lincoln was free from usual official vanity. He, on the contrary, abhorred it. He avoided referring to his official title of Mr. President and generally referred to his office as 'this place'.

Once he pleaded with some old friends who insisted on addressing him as Mr. President, "Now call me Lincoln, and I promise not to tell of the breach of etiquette."

Lincoln used to tell stories of his ugliness to others. One of his favourites was as follows.

A stranger accosted me and said, Excuse me, sir, I have a present for you. "What is it?" I asked. He placed a knife in my hands and said he was asked to keep it until he found a man uglier than himself.

Once when Mr. Lincoln was polishing his shoes in the basement of the White House, he had a visitor who was astonished to see the President of the United States doing such a menial task.

"What! Mr. President," he exclaimed, "are you polishing your own shoes?"

"Who else should I be polishing?" Lincoln asked.

Shri Madan Mohan Malvia was once asked by a politician how Banaras University had, in its short life, gained the prestige as one of the greatest storehouses of knowledge in the nation.

"In all likelihood," said Malviya slyly, "it is because the young entrants bring so much of it, and the final-year students take away so little."

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