Annexure-V_18th NPC

Report of the Committee on Guidelines/ Procedure for Implementation of TWFL Technology



GOVERNMENT OF INDIA
MINISTRY OF POWER
CENTRAL ELECTRICITY AUTHORITY

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List of Abbreviations

ADC	:	Analog-to-Digital Converter
AI	:	Artificial Intelligence
AMC	:	Annual Maintenance Contracts
CEA	:	Central Electricity Authority
CTUIL	:	Central Transmission Utility of India Limited
EHV	:	Extra High Voltage
HVAC	:	High Voltage Alternating Current
HVDC	:	High Voltage Direct Current
ISTS	:	Inter-State Transmission System
MSETCL	:	Maharashtra State Electricity Transmission Company Limited
NER	:	North Eastern Region
NERPC	:	North Eastern Regional Power Committee
NRLDC	:	Northern Regional Load Dispatch Centre
NRPC	:	Northern Regional Power Committee
NPC	:	National Power Committee
OEM	:	Original Equipment Manufacturer
OPGW	:	Optical Ground Wire
PGCIL	:	Power Grid Corporation of India Limited
PSE&TD	:	Power Systems Engineering & Technology Division
SCADA	:	Supervisory Control and Data Acquisition
SOTF	:	Switch-On-To-Fault
TDR	:	Time Domain Reflectometry
ToR	:	Terms of Reference
TW	:	Travelling Waves
TWFL	:	Travelling Wave Fault Locator
UHV	:	Ultra High Voltage
UPS		Uninterruptible Power Supply

1. Introduction

1.1 Background

Reliable and fast identification of faults on transmission lines is essential for maintaining the security and reliability of the Power System and for reducing the time required for restoration of supply. At present, transmission line faults are primarily detected and located through conventional impedance-based distance protection systems. These systems estimate the apparent impedance between the relay location and the fault point and determine the fault location based on the measured electrical quantities. The accuracy of impedance-based fault location is influenced by the electrical characteristics of the fault and the transmission system. In particular, fault resistance and the associated changes in the electrical parameters of the line and fault path can affect the apparent impedance seen by the relay. Changes in the condition of line insulation, including deterioration of insulators, may also alter the electrical characteristics of the fault path and consequently affect the measured R, L and C parameters. Such variations may result in errors in fault-location estimation and may affect the performance of conventional impedance-based protection, particularly in cases involving high-resistance or developing faults. These limitations of impedance-based fault-location methods highlight the need for a more accurate and faster fault-location approach, for which Travelling Wave Fault Locator (TWFL) technology offers a significant technical advantage.

Travelling Wave Fault Locator (TWFL) technology are mainly of two types i.e. On-line TWFL and Off-line TWFL. These TWFL technologies follow a different principle for locating faults in comparison to conventional Impedance based Relay. On-line TWFL identifies and locates the fault by detecting the travelling-waves associated with high-frequency electro-magnetic transients that get generated during fault on the line. By analyzing the arrival time of travelling waves and their reflections, the location of the fault is calculated. In case of Off-line TWFL, a pulse is sent into the into de-energized lines and the time taken by reflected wave is measured to compute the distance of fault location. Thus, the method of TWFL technologies is based primarily on the propagation characteristics and time-domain behavior of the travelling wave rather than on the impedance measured at the relay location. The TWFL principle provides an important technical advantage for accurate fault location, particularly where the apparent impedance may be affected by fault or system conditions. Accordingly, TWFL can provide more accurate and rapid fault-location information and is less dependent on factors such as fault resistance and variations in apparent impedance, making it a technically superior approach to conventional impedance-based fault-location methods. Its application can improve the accuracy and speed of fault location, assist in faster restoration of transmission lines and provide additional information regarding developing or abnormal line conditions. In view of these advantages, it becomes pertinent to examine the suitability of TWFL for deployment on critical transmission lines for improving the overall reliability and operational efficiency of the transmission system.

1.2 Committee Constitution

In the 17th National Power Committee (NPC) meeting held on 27.02.2026 at Vizag, Andhra Pradesh, NRPC Sub-Group's Report on Implementation of TWFL was discusses, wherein it was decided that the matter merits bringing out a uniform National Policy Framework for TWFL,

and accordingly the matter was referred to PSE&TD Division of CEA to prepare suitable Guidelines/Procedure for implementation of TWFL on critical transmission lines at 220 kV and above, and at 132 kV and above in the North-Eastern Region.

In this context, to examine and prepare Guidelines/ Procedure for implementation of TWFL Technology, a Committee was constituted vide CEA letter dated 13.05.2026 (**Annexure-I**). The details of the Committee Members are given as under:

1	Sh. N.R.L.K. Prasad, Chief Engineer (PSE&TD Division), CEA	Chairperson
2	Sh. Om Kishor, EE, NRPC	Member
3	Sh. V. Muncha, Director, NERPC	Member
4	Sh. P. P. Chand, DGM, GRID INDIA Sh. Deepak Kumar, Dy. Manager, GRID INDIA	Member
5	Sh. Anurag, GM , Engg-SS, PGCIL	Member
6	Sh. Manoj Joshi, Superintending Engineer (ACI&P), MSETCL	Member
7	Sh. Pankaj Kumar Verma, Dy. Director (PSE&TD Division), CEA	Member Convener

The Terms of Reference (ToR) of the Committee are as under:

(a) To explore various On-line and Off-line fault locator technologies including TWFL.
(b) To assess the indigenous availability of the various Fault Locator Technologies.
(c) Cost comparison of various Fault Locator Technologies of Fault Locator.
(d) To prepare Guidelines/Procedure for implementation of Fault Locator Technologies on critical Transmission Lines for 220 kV and above (132 kV and above for NER) voltage levels.
(e) Any other relevant issues.

1.3 Proceedings of the Committee

The Committee conducted two meeting to deliberate on the matter. The first meeting was held on 25.05.2026. Owing to the evolving nature of the subject matter, the Committee invited various OEM's in the TWFL field for gaining valuable insights. In the meeting, TWFL technologies available with OEMs {M/s GE Vernova, M/s Taurus MK Srinivasan Systems Pvt. Ltd. [mentioned as Taurus-MKS in ensuing sections] and M/s Megger (India) Pvt Ltd [mentioned as Megger in ensuing sections]} including their technical features (On-line TWFL Technology vs Off-line TWFL Technology), indigenous availability, manufacturing capacity, cost, field experience and effectiveness were discussed. The integration of TWFL with the existing protection systems and other relevant technical issues were also discussed. NRPC Committee Report on TWFL implementation was also discussed in the meeting. The minutes of the first meeting are enclosed at **Annexure-II.**

Following the first meeting, technical and operational queries were formulated and forwarded to the OEMs, and the responses received regarding On-line and Off-line TWFL technologies were compiled and circulated to the Committee members. The second meeting was convened on 27.08.2026 to examine the responses received from the OEMs, deliberate on the deployment of TWFL technology (On-line/Off-line), and discuss the criteria for identification of critical transmission lines for deployment of TWFL. The minutes of the second meeting are enclosed at **Annexure-III**.

Based on the deliberations held, and all relevant information made available, the Report has been structured to address the following aspects:

- Takeaway from NRPC Sub-Group Committee Report on TWFL
- Details of On-line TWFL Technology
- Details of Off-line TWFL Technology
- Comparative Assessment of On-line and Off-line TWFL Technology
- Guidelines/Recommendations for TWFL Technology

Ensuing sections discuss the above in sufficient detail.

2. Take-away from NRPC Sub-Group Committee Report

(a) Brief Background

Based on a proposal of PGCIL placed before the 80th NRPC meeting for deployment of TWFL on critical transmission lines, NRPC constituted a Sub-Group comprising representatives from CEA, CTUIL, NRLDC and other stakeholders to assess the technology and identify critical transmission lines warranting TWFL installation. The Sub-Group examined the matter through detailed deliberations involving the concerned transmission and system operation stakeholders, including assessment of the technical features and field performance of TWFL. A physical visit was also undertaken to the 765/400 kV Meerut Substation on 19.09.2025 by a team comprising members from CEA, NRLDC, CTU and NRPC Secretariat to understand the functioning of TWFL and evaluate the benefits of its installation. However, it may be mentioned that the Sub-Group primarily focused on regional requirements and did not cover lower voltage levels, particularly 132 kV lines relevant to the North-Eastern Region.

(b) Operational and System Level Benefits

NRPC Sub-Group observed significant technical and operational advantages of TWFL in providing accurate fault-location information and reducing the time required for fault identification and restoration. Report mentioned that TWFL systems consistently achieve fault location accuracy within ±100–500 meters, even on long transmission lines exceeding 300 km, mixed overhead–underground lines, and lines with series compensation or shunt reactors. The technology can reduce the area and time required for physical patrolling and thereby support faster restoration of critical transmission lines. The deployment of TWFL therefore provides tangible operational benefits, including significant reduction in outage duration, improved system availability, enhanced reliability indices and reduced manual patrolling effort. Faster restoration directly contributes to grid security, particularly for lines evacuating renewable and nuclear power, where prolonged outages can lead to generation backing down and grid instability.

(c) Deliberations and Analysis

The field observations also provided a comparison with the fault-location indications obtained from conventional Main-1/Main-2 distance relays and those obtained from TWFL. In a number of cases, the conventional distance relay indications showed deviations of several kilometers from the actual fault location, with mismatches of approximately 6–20 km reported in some instances. Such deviations can result in a larger section of the transmission line having to be patrolled before the fault is identified and rectified. The Sub-Group therefore observed that more precise fault-location information can contribute to reduction in restoration time, particularly in the case of long transmission lines and lines located in difficult terrain. NRPC Report further explained that conventional distance relays are impedance-based and their fault-location indication depends on line impedance parameters and system conditions. In contrast, TWFL determines the fault location by detecting the arrival times of travelling waves at the line terminals and is inherently independent of line impedance parameters, fault resistance and power-flow conditions.

(d) Availability and Operational Cost

The NRPC report mentions that On-line TWFL devices manufactured by GE and Qualitrol are currently available in the Indian market. In addition, TWFL devices manufactured by SEL and Kehui are also available globally. Also, as per the report, the indicative cost of TWFL systems, including supply, installation, testing and commissioning, ranges approximately from ₹18 lakh for a single-line module to ₹100 lakh for an eight-line module. The actual cost may vary depending upon the number of transmission lines covered, system configuration and site-specific requirements. It is noted that NRPC report focused on On-line TWFL technology and does not mention about Off-line TWFL technology.

(e) Recommendation

The Sub-Group considered long lines, hilly-terrain lines, renewable and nuclear evacuation lines, and other operationally important corridors as suitable for priority consideration. It recommended a phased approach for implementation of TWFL, rather than immediate deployment on all transmission lines. Such an approach would enable the technology to be initially implemented on lines having higher operational criticality and greater restoration challenges, followed by wider deployment based on field experience, performance assessment and operational requirements.

Accordingly, For the first phase, the recommended criteria included:

(i) 220 kV, 400 kV and 765 kV transmission lines longer than 200 km;
(ii) 220 kV, 400 kV and 765 kV transmission lines used for evacuation of renewable and nuclear power having length more than 150 km;
(iii) 220 kV and above transmission lines located in hilly terrain; and
(iv) Inter-regional 220 kV and above transmission lines having length more than 150 km.

Based on the overall assessment, the Sub-Group highlighted the need for formulation of a national-level policy and detailed implementation guidelines for systematic deployment of TWFL Technology.

3. Details of On-line TWFL Technology

3.1 Technical Details of On-line TWFL Technologies

On-line Travelling Wave Fault Locator (TWFL) technology operates on the principle that a fault on a transmission line causes an abrupt collapse of voltage and surge in current, generating high-frequency electromagnetic transients known as "travelling waves." These waves propagate along the transmission line simultaneously in both directions from the point of fault, at velocities approaching the speed of light (approximately 3 x 10^5 km/s for overhead lines). The frequency content of these waves lies in the range of approximately 100 kHz to 500 kHz.

An On-line TWFL system continuously monitors the transmission line for such high-frequency transients during normal energized operation. When a fault occurs, the system at each end of the line records the precise GPS-synchronized timestamp at which the travelling wave front arrives. Using these two timestamps and the known total line length, the fault location is computed automatically without any manual intervention. A typical schematic of On-line Travelling Wave Fault Locator is shown in **Figure-1**.

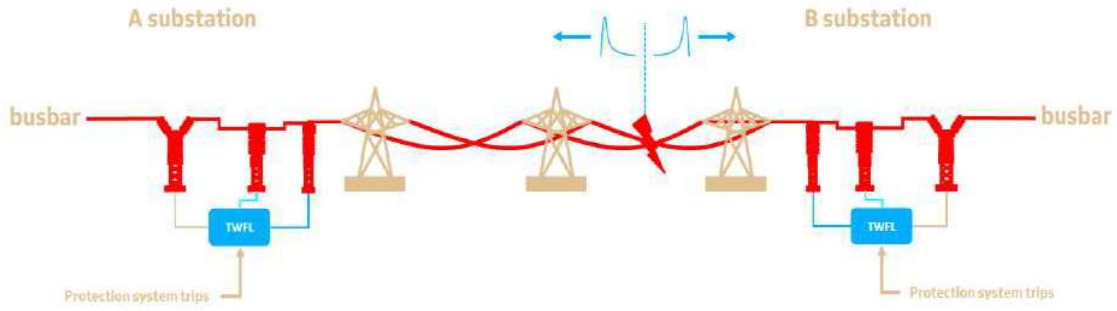


Figure 1: Typical schematic of On-line Travelling Wave Fault Locator

TWFL solution consists of the high-speed travelling-wave acquisition units, time-synchronization equipment, Central processing unit, communication interface and DR Manager software. The System is stated to provide typical fault location accuracy of less than 150 meters with automatic fault location capability and SCADA integration support.

There are two types of technologies exists in On-line TWFL. These area as follows.

1. Single ended TWFL technology
2. Double ended TWFL technology

3.2 Single ended TWFL Technology

In case of Single ended TWFL, the setup is installed only at one end. On the occurrence of a fault, TW travel in both the direction. The system uses the travelling wave received directly from the fault (TW reaching directly to the Setup) and reflections of TW from the remote end of the line (Other end Substation). Based on the timing of reaching of direct TW, reflected TW and length of the line, the distance of fault location is measured.

The principal advantage of single ended TWFL technology is that equipment is required only at one terminal. However, since the technology rely on the detection of the direct pulse and the reflected pulse from other end Substation, the reflected pulse gets attenuated and therefore, depending on the type of fault and the distance from the measurement point the accuracy of fault detection varies. The accuracy is generally lower than that of a double-ended system because the calculation relies on identification of reflected waves, which may become difficult under certain line and network conditions. Further, since single ended TWFL relies on the reflected pulses, therefore, depending on where the fault happened, it might have a superposition of the direct pulse and the reflected pulse, which leads to almost impossible to locate the fault. Further, non-linear lines (Hybrid lines or Railways) will have multiple reflections not related to the fault which invalidates its method for such conditions.

3.3 Double ended TWFL Technology

Double ended TWFL relies only on the arrival of the direct pulse generated by the event in each Substation end. In case of the Double ended TWFL, complete setup consisting of a central processing unit, acquisition unit, GPS receiver and DR Manager software is installed at both ends of the transmission line. The acquisition units capture high-frequency signals, while the GPS provides accurate time synchronization. Communication between the two Substations through an Ethernet link is necessary for exchange of travelling wave records required for double-ended fault calculation. A typical schematic diagram of Double ended TWFL technology is shown in **Figure-2**.

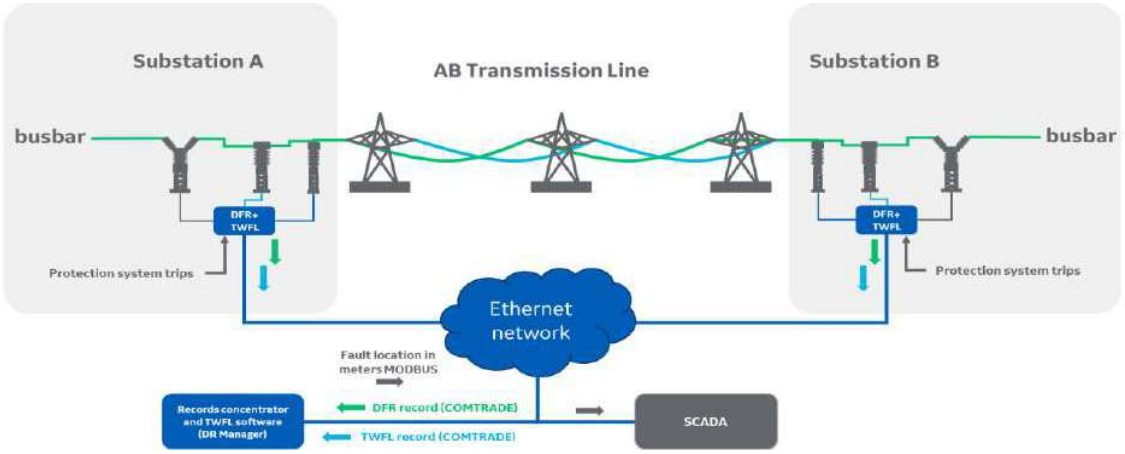


Figure 2: Typical schematic diagram of Double ended TWFL technology

The distance to fault can be calculated by following formula.

$$X_{\mathrm{Distance\,to\,fault}} = \frac{\mathrm{l{+}k{\cdot}c{\cdot}(ta{-}tb)}}{2}$$

Where $l-linelength$
$c-lightspeed$
$k-velocityfactor$

ta–$wavehead\ timestamp\ T_a$
tb–$wavehead\ timestamp\ T_b$

Simpler and more accurate algorithms can be applied using Double ended TWFL since the direct pulse is easier to identify than the reflected pulse. Some of the advantage of Double ended TWFL are as follows:

a) Double Ended TWFL is suitable for all type of applications.
b) Switch-On-To-Fault (SOTF) can only be located for all occasions by Double Ended Method.
c) Each mixed section generates (Over Head and Underground) a non-linearity in the line and reflections. In such case only Double ended TWFL is suitable.
d) Reflections can travel through all segments making it hard to automatically locate the fault with Single Ended.
e) Since Auto-Transformers impact generating reflections. Therefore, Double ended TWFL is more suitable technology.

A Comparison of Single-Ended vs. Double-Ended On-line TWFL configurations has been shown in **Table 1**.

Aspect	Single-Ended	Double-Ended (Preferred)
Equipment Location	One end only	Both ends of the line
Accuracy	Lower; depends on reflected pulse quality	Higher; relies on direct pulses only
GPS Synchronization	Not required	Mandatory (nanosecond precision, IRIG-B)
Communication	Not required	Required between both ends
Limitations	Reflected pulses may be attenuated on long/mixed lines; unreliable for short lines and T-connections	Requires dedicated communication; OPGW path may be affected during fault
Preferred Application	Basic / backup configuration	EHV/UHV systems; all critical applications

Table 1: Comparison of Single-Ended vs. Double-Ended On-line TWFL configurations

It is observed by the Committee that Double-ended methods are preferred over single-ended methods because they rely only on direct travelling wave pulses and provide better accuracy, whereas single-ended methods depend on reflected pulses which may become difficult to identify accurately.

3.4 System Architecture and Components of On-line TWFL Technology

The On-line TWFL system generally comprises the following core components:

- GPS Receiver: Provides precise time synchronization.
- Remote Data Acquisition Module: Samples high-frequency signals at 5 MHz (one acquisition every 200 nanoseconds). Monitors voltage analog signals (Phase A, B, C, Neutral) and various digital signals (Breaker operation, TRIP, Various Protection Operation Status Signals).

- Central Processing Unit: Interfaces with multiple Data Acquisition units. Communicates with SCADA via Modbus and IEC 60870-5-104 protocol.
- DR Manager Software: Software manages Disturbance Records from multiple devices. Communicates via TCP/IP.
- GPS Synchronization and Communication Requirements**:** Precise GPS synchronization is the critical enabling requirement for double-ended On-line TWFL. Communication links between both substations must be dedicated and isolated. However, public internet is not recommended for protection-grade applications. OPGW-based communication paths may be adversely affected during a fault event, therefore a dedicated and secure communication arrangement through an independent medium is strongly recommended.

3.5 Indigenous Availability of the Technology

As of now there are two manufacturers who are supplying On-line TWFL technology in India. These are as follows:

(a) GE Vernova
(b) Qualitrol

Both the above mentioned manufacturers are not manufacturing the Product in India. GE Vernova is manufacturing the product at GEV factories located in Brazil and UK. GE Vernova is manufacturing approximately 1500 RPV311 and RA333 per year globally while Qualitrol is manufacturing approximately 300 devices per year. The system is designed for an industrial service life around 15-20 years, provided that standard maintenance and operating conditions as recommended by the manufacturer. Both the above manufacturers are able to supply in India on the requirement of the Product.

Other suppliers of On-line TWFL technologies include (a) SEL (Schweitzer Engineering Laboratories), and (b) Kehui. However, they have limited India-specific deployment data.

A comparison of OEMs offering On-line TWFL products available in the Indian market have been shown in **Table 2**.

Manufacturer	Product / System	Manufacturing Location	Status in India
GE Vernova	RT430, RPV311, RA333, DR Manager	Brazil and UK	Widely deployed; 200+ lines in India
Qualitrol	TWS FL-8 / TWS FL-1	Not manufactured in India	Available through authorized channel partners

Table 2: OEMs offering On-line TWFL products available in the Indian market

4. Details of Off-line TWFL Technology

4.1 Technical Details of Off-line TWFL Technology

Off-line TWFL technology relies basically on Time Domain Reflectometry (TDR). It is like radar i.e. a pulse is sent into the into de-energized lines and the time taken by reflected wave is measured to compute the distance of fault location. The transmission line must be de-energized, isolated, and grounded at both ends before testing. A typical example of Off-line TWFL connection is given in **Figure-3**.

Every transmission line possesses distributed electrical parameters namely resistance (R), inductance (L), capacitance (C) and conductance (G). These parameters define the characteristic impedance and travelling wave propagation characteristics of the line. When a fast impulse is injected into a transmission line, a travelling wave propagates along the conductor at a velocity close to the speed of light. When the travelling wave front encounters any impedance discontinuity - an actual fault (open or short circuit, high resistance), a physical discontinuity (jumper, repair sleeve, joint), or an abnormality (corrosion, insulator degradation, vegetation contact) - a portion of the pulse energy is reflected back towards the injection terminal. The round-trip travel time of this reflected wave is measured precisely, and the distance to the discontinuity is computed using the known wave propagation velocity.

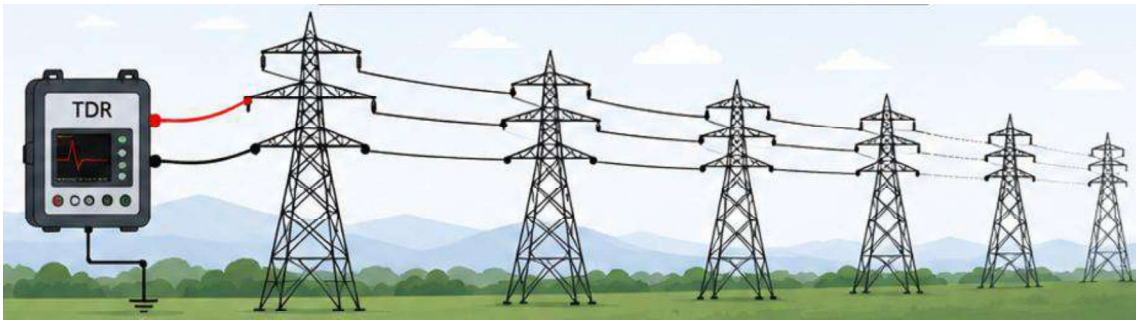


Figure-3: Off-line TWFL connection to Transmission Line

Typical impedance discontinuities include following:

(a) Broken conductors
(b) Conductor-to-earth faults
(c) Phase-to-phase faults
(d) Loose jumpers
(e) Corroded conductors
(f) Damaged insulators
(g) Tree encroachments
(h) Excessive sag
(i) Weak points developing along the line

In addition to determining fault distance, the Off-line TWFL analyzes the polarity, magnitude and waveform shape of the reflected travelling waves and therefore is capable of detecting

the nature of the fault like permanent open circuit, short circuit faults, high impedance fault and their location. Different types of defects produce unique travelling wave signatures:

• Open circuit faults generate positive reflections.
• Short circuit faults generate negative reflections.
• High resistance faults produce reduced amplitude reflections.
• Progressive insulation deterioration produces gradual signature variations.
• Tree encroachments and external objects alter line capacitance and generate identifiable travelling wave responses.

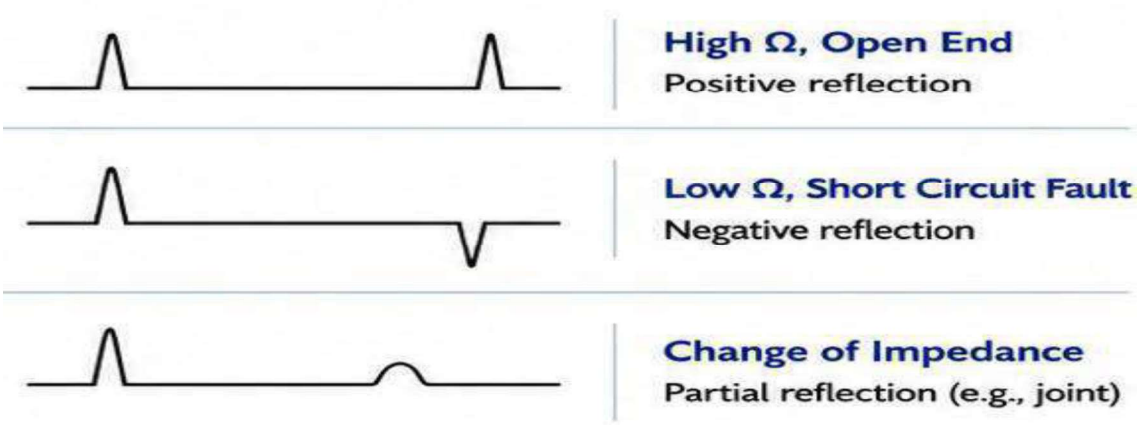


Figure 4: Pattern of Reflection of Pulse based on the Fault Condition

The system therefore provides not only fault location but also the fault characterization. Off-line TWFL technology.

Unlike On-line TWFL, Off-line TWFL systems are portable and can be deployed at any substation within a utility network. The standard deployment process involves:

(a) De-energization and isolation of the faulted line
(b) Transportation of the Off-line TWFL equipment to the relevant substation
(c) Connection via surge arrestor terminals using specially designed hot-sticks
(d) Grounding verification and safety checks
(e) Pulse injection and waveform acquisition
(f) Analysis and fault distance computation

The Off-line TWFL technology combines both fault location and line signature analysis functions within a single unit, thereby enabling not only fault identification during breakdown conditions but also predictive analysis of developing defects and insulation weaknesses.

The equipment in the Off-line TWFL technology includes onboard display, onboard analysis capability and graphical representation of test results. The System works on the principle of signature analysis, wherein reference signatures of transmission lines can be recorded during healthy conditions and subsequently compared with later measurements taken during periodic maintenance activities. By comparing the signatures over time, utilities can identify developing insulation weaknesses, loose connections and line irregularities before they evolve into major faults. The trend comparison allows utilities to understand the progression

of faults and deterioration in the transmission line system. The system is capable of identifying:

a) Existing faults
b) Developing faults
c) Weak insulation points
d) Defective insulator strings
e) Abnormal conductor conditions
f) Potential flashover locations

This enables utilities to adopt predictive and preventive maintenance practices.

As of now there are two OEMs supplying Off-line TWFL technology in India. These are as follows:

(a) Taurus-MKS
(b) Megger

The Taurus-MKS system injects a controlled high-voltage impulse of up to 20 kV into the de-energized transmission line and measures the reflected travelling waves returning from various discontinuities. The elapsed time between pulse injection and receipt of reflected travelling waves is measured with high precision. Based on travelling wave propagation characteristics, the distance to the discontinuity is calculated. The product can cover the line length up to 800 km. The claimed fault location accuracy of the system is within ±100 meters.

In case of Megger the solution injects test pulses of up to 1500 volts with operating frequencies ranging from approximately 100 kHz to 2 MHz. The System support testing and fault location for transmission line lengths of more than 1000 km. The claimed fault location accuracy of the system has been close to 20 meters.

Off-line TWFL has following advantages:

- Single-ended operation;
- No requirement for equipment at the remote end;
- No requirement for GPS synchronization;
- No dependence on communication links;
- No dependence on protection-relay operation;
- Portability;
- Possibility of use on multiple lines;
- Suitability for planned maintenance;
- Capability for line diagnostics and preventive maintenance; and
- Comparatively lower infrastructure requirement.

Its principal limitation is that the line must be in de-energized condition before the equipment is connected and the test pulse injected. Therefore, it is not capable of providing immediate automatic fault location on an energized line. The Committee also noted that operation during rainy conditions may sometimes become time-consuming because of difficulties associated with grounding.

4.2 Indigenous Availability of the Technology

Taurus-MKS, Off-line TWFL has designed, engineered and manufactured the product in India. The pulse generation system, travelling wave acquisition hardware, signal processing algorithms, diagnostic software and fault analysis techniques have been developed in house. The product is not based on any imported licensed technology and is fully supported from India. The company possesses indigenous capabilities for design, manufacturing, calibration, testing, commissioning, training and after-sales support. Manufacturing and servicing are carried out from the company's Bangalore facility. Taurus-MKS has an annual production capacity of approximately 400 units per annum. The manufacturing capacity can be further enhanced to 1000 units annually, based on utility requirements and project demand.

Megger is supplying TWFL technology through its Mumbai Office, with local technical support and service capabilities. While the technology and manufacturing are supported by Megger's global facilities in the UK, Germany, USA, Sweden, and India, the product is available for indigenous deployment and utility-scale applications across the country. Megger is capable of production of more than 200 units/year and plant capacity is available to meet more than 500 units.

A comparison of indigenous capability of Taurus-MKS and Megger is shown in **Table 3**.

Manufacturer	Product	Manufacturing Location	Indigenous Status
Taurus-MKS	Taurus-MKS EHT-1250 MAX-3 / MAX-4	Bangalore, India	Fully Indigenous (Make in India); in continuous development since 1989
Megger	Portable TDR-based Off-line TWFL System	UK, Germany, USA; Mumbai office in India	Partially Indigenous (local support and service)

Table 3: OEMs offering Off-line TWFL products in the Indian market

5. Comparative Assessment of On-line and Off-line TWFL Technology

5.1 Details of TWFL Technologies

TC-TWFL Committee sought the inputs from the OEMs of both the TWFL technologies. The Inputs w.r.t. details of TWFL Technologies are summarized in the **Table-4**.

Parameter	GE Vernova (On-line)	Qualitrol (On-line)	Megger (Off-line)	Taurus-MKS (Off-line)
Technology Type	On-line, Double-ended / Single-ended	On-line, Double-ended (auto) / Single-ended (manual)	Off-line, Portable, Single-ended (TDR)	Off-line, Portable, Single-ended (TDR+TW)
Sampling Rate	5 MHz (200 ns resolution)	Up to 20 MHz (12-bit ADC)	Not applicable (TDR pulse)	Not applicable (TDR pulse)
GPS/Time Sync Required	Yes - IRIG-B, sub-100 ns; existing GPS usable if compliant	Yes - own internal GPS module mandatory; existing substation GPS cannot be used	No GPS required	No GPS required
Claimed Accuracy	Typically <150 m;	+/- 60 m (double-ended automatic)	~ +/- 20 m	+/- 100 m (normal field conditions)
Line De-energization Required	No (operates on energized line)	No (operates on energized line)	Yes (line must be de-energized and isolated)	Yes (line must be fully de-energized and isolated)
Pulse Injection Voltage	N/A (passive monitoring)	N/A (passive monitoring)	Up to 1,500 V (peak); min 300 V/ 1500 V at 300 Ohm	Up to 20 kV impulse (high voltage for long EHV lines)
Power Supply	100-250 Vdc / 110-240 Vac (existing station auxiliary DC supply)	(AC/DC supply)	AC mains 230 V or external battery	Battery operated; upto 6 hours capacity
Space Requirement	RPV311: 3U 19-inch rack; RA333: 5U half-19-inch rack per line	3U high 19-inch rack chassis	Portable; no permanent installation	3 rugged waterproof cases (~25-30 kg each); no permanent installation

Parameter	GE Vernova (On-line)	Qualitrol (On-line)	Megger (Off-line)	Taurus-MKS (Off-line)
Diagnostic Capability	Fault location only	Fault location only (Grid Assist in development)	Fault location + signature analysis + diagnostics	Fault location + AI-assisted diagnostics + predictive maintenance
HVDC Applicability	Yes; globally deployed on HVDC	Yes; applicable	Not applicable (Off-line, not for energized HVDC)	Yes; deployed on Talcher-Kolar, Agra, Pugalur, Kurukshetra HVDC; BMTE Brazil (2,544 km)
Expected Lifespan	>20 years	15 years	8-12 years (with periodic maintenance)	>15 years (product in use since 1990)
Communication Required	Yes (dedicated, isolated network; TCP/IP)	Yes (dedicated network)	No	No

Table 4: Comprehensive comparison of TWFL technologies across OEMs

The Committee concluded that On-line TWFL is preferable for highly important transmission corridors where rapid restoration through automatic fault identification is required, whereas Off-line TWFL is particularly suitable where portability, multi-line utilization, diagnostics and lower infrastructure requirements are important. **Table-5** provides a comprehensive comparison of On-line and Off-line TWFL technologies as evaluated by the TC-TWFL Committee:

Parameter	On-line TWFL	Off-line TWFL
Operating condition	Energized line	De-energized line
Principle	Detects naturally generated fault travelling wave	Injects controlled pulse and analyses reflection
Fault-location operation	Automatic	Generally manual/non-automatic
Line shutdown	Not required	Required
External pulse	Not required	Required
Remote-end equipment	Required for double-ended system	Not required

Parameter	On-line TWFL	Off-line TWFL
GPS synchronization	Required for double-ended systems	Not required
Communication link	Required for double-ended system	Not required
Protection relay dependency	Can be integrated/interface with relay/DFR system	Not required
Portability	Permanently installed/configured	Portable
Multiple-line use	Generally configured for designated lines	One unit can serve multiple lines
Diagnostic capability	Primarily fault location	Fault location plus diagnostic/preventive maintenance capability
Restoration advantage	Very high because location can be obtained automatically after fault	Lower because equipment must be mobilized and line isolated
Infrastructure requirement	Relatively high	Relatively low

Table 5: Comprehensive comparison of Off-line and On-line TWFL technologies

5.2 Indigenous Availability of TWFL

W.r.t. Indigenous availability of the technology, the Committee has observed following:

(a) GE Vernova

GE Vernova stated that its TWFL equipment is manufactured at its factories in Brazil and the UK. The technology is available in India with local support. The stated annual manufacturing capacity is approximately 1500 RPV311 and RA333 units.

Thus, the technology is available for deployment in India but is not manufactured in India, based on the information furnished.

(b) Megger

Megger stated that its TWFL technology/ manufacturing is supported through its global facilities, including India, UK, Germany, USA and Sweden. Local technical support and service capability are available through Megger. The annual manufacturing capacity stated was more than 200 Units/ year, with plant capacity available to meet more than 500 units.

(c)Taurus-MKS

Taurus-MKS is observed to be completely indigenous. The product has been designed, developed, patented and manufactured entirely in India, with continuous development since 1989 through its in-house R&D facility.

The company has stated an annual manufacturing capacity of approximately 400 units, which can potentially be enhanced to approximately 1000 units/year depending upon demand.

(d) Qualitrol

Qualitrol has stated that its TWFL products are not manufactured in India, although they are available through authorized Indian channel partners and spares can be maintained locally.

Accordingly, from the perspective of indigenous manufacturing, Taurus-MKS provides the indigenous produced products, whereas the other products are internationally manufactured products available for deployment and support in India. A comparison of indigenous manufacturing capacity has been shown in **Table-6**.

OEM	Product Type	Indigenous Status	Details
Taurus-MKS	Off-line TWFL	manufactured in India	Designed, developed, patented, and manufactured entirely in India since 1989. Bangalore facility. DSIR-recognized in-house R&D. NSIC registered. Manufacturing capacity: 400 units/year (expandable to 1,000). Supports Make in India initiative.
Megger	Off-line TWFL	Not manufactured in India	Megger has presence in India with Mumbai office providing local technical support and service. Global manufacturing in UK, Germany, USA, Sweden. Local assembly and customization possibilities. Manufacturing capacity: 200+ units/year, expandable to 500+.
GE Vernova	On-line TWFL	Not manufactured in India	Manufactured at GE Vernova factories in Brazil and UK. Available in India through local sales channels. Global manufacturing capacity: approximately 1,500 RPV311 and RA333 units per year.
Qualitrol	On-line TWFL	Not manufactured in India	Not manufactured in India. Available through authorized channel partners who maintain spares stock. Global manufacturing capacity: approximately 300 devices per year.

Table 6: Indigenous availability assessment of TWFL products

5.3 Indicative Per Unit Cost of TWFL

The Cost of TWFL technologies of various OEMs is shown in **Table-7**.

Product/Technology	Type	Indicative Cost	Remarks
GE Vernova	On-line	Approx. ₹18 lakh for single-circuit/single-line module; approx. ₹1 crore for eight-line module*	Includes supply, installation, testing and commissioning as per NRPC presentation
Megger	Off-line	Approx. ₹45 lakh + taxes	HVAC; complete OLTS system
Taurus-MKS	Off-line	Approx. ₹55–65 lakh/set	HVAC, 66–800 kV; depends on configuration/ accessories
Qualitrol	On-line	Available in Indian currency through authorized channel partners; detailed quotation on request	Cost is scheme/ configuration dependent

Table 7: Indicative per unit cost of TWFL products

*The NRPC Sub-group indicated an approximate cost of ₹18 lakh for a single-circuit/single-line On-line module and approximately ₹1 crore for an eight-line module, inclusive of supply, installation, testing and commissioning for the cost of GE Vernova.

5.4 Details of the Utilities where TWFL has been deployed

GE Vernova:

GE Vernova reported a mature global installed base and stated that its equipment has been installed on more than 200 lines in India. Some of the lines where GE Vernova TWFL has been deployed are shown in **Table-8**.

Substation	Feeder/Line	Voltage
Meerut	Meerut–Bhiwani	765 kV
Meerut	Meerut-Moga	765 kV
Meerut	Meerut-Koteshwar- I/II	765 kV
Jeypore	Jeypore-Gukuwaka-I/II	400 kV
Ranchi	Ranchi-Sipat 2	400 kV

Table 8: GE Vernova TWFL deployed Lines

Megger:

Representative from Megger furnished following UPPTCL lines from Sarnath where their TWFL System has been deployed:

- Sarnath–Anpara L-5: approximately 158.341 km;
- Sarnath–Anpara L-6: approximately 262.267 km;
- Sarnath–Prayagraj: approximately 130 km;
- Sarnath–Gorakhpur: approximately 218 km; and
- Sarnath–Obra: approximately 145 km.

Taurus-MKS:

Taurus-MKS stated that its Off-line TWFL was first supplied in 1990 and has since been used by several Indian utilities, including PGCIL, APTRANSCO, TSTRANSCO, KPTCL, TANTRANSCO, KSEB, MPPTCL, UPPTCL, WBSETCL, DVC, HVPNL, and Adani Transmission.

Further, the technology has also been implemented by Nepal Electricity Authority, Bhutan Power Corporation and BMTE, Brazil.

Specific Indian examples include:

- 220 kV Kadarpur–Pali transmission line of HVPNL;
- 400 kV Allahabad–Singrouli Transmission Line-3 of Powergrid; and
- 132 kV Panyor Lower–Itanagar transmission line in Arunachal Pradesh.

Taurus-MKS also furnished examples from Arunachal Pradesh and Tripura, including lines in the range of approximately 30–95 km.

Taurus-MKS also reported application on major HVDC projects including:

- Talcher–Kolar HVDC;
- Agra HVDC;
- Pugalur HVDC; and
- Kurukshetra HVDC.

The technology was stated to have been used on these systems for more than 15 years.

Qualitrol:

Qualitrol has supplied its TWS systems to utilities internationally. The reference customers are Public Service New Mexico, CenterPoint Energy, Dominion Virginia, Eskom, Saudi Electricity Company, Svenska Kraftnät, and Scottish Power.

The furnished information indicates voltage levels from 66 kV to 500 kV, with automatic double-ended analysis capable of approximately ±60 m accuracy under good signal conditions.

5.5 Effectiveness of the TWFL Product (based on feedback from respective customers)

On-line TWFL

The NRPC field assessment provides strong evidence of the effectiveness of On-line TWFL technology in Indian transmission networks. The observed difference between On-line TWFL

fault-location indications and actual physical fault locations was generally within approximately one tower span or around 0.5 km. In comparison, conventional Main-1/Main-2 relay indications differed by approximately 6–20 km in some cases. The principal operational benefits identified were:

- reduction in outage duration;
- faster restoration;
- reduction in manual patrolling;
- improvement in system availability;
- improvement in reliability indices; and
- improved grid security.

These benefits are particularly relevant for renewable-energy evacuation corridors and transmission lines associated with nuclear generation, where prolonged outages may result in generation backing down and adverse system consequences.

Off-line TWFL

The OEM responses indicate successful field deployment of Off-line TWFL over several decades. Taurus-MKS reported successful use from 66 kV to 765 kV and under diverse terrain and environmental conditions, including forests, mountainous regions, coastal areas and long-distance transmission corridors. User feedback indicates:

- rapid identification of fault locations;
- reduction in fault-patrolling time;
- reduced outage duration;
- reduced manpower requirements;
- faster restoration;
- detection of developing faults;
- detection of insulator abnormalities;
- detection of tree encroachment and conductor defects; and
- support for preventive and predictive maintenance.

5.6 Limitation of the TWFL Products

(a) Limitations Regarding Line Length

- GE Vernova: Travelling wave amplitude decreases with increasing line length due to attenuation; however, this is mitigated by the 5 MHz high-resolution acquisition and sensitive detection algorithms.
- Megger: Suitable up to approximately 1,000 km; very long and complex networks may require synchronized measurements from both ends.
- Taurus-MKS: As line length increases, reflected signal amplitude decreases. This has been mitigated by high-voltage impulse injection (up to 20 kV) and sensitive signal acquisition electronics. The Technology is applicable up to 800 km (HVAC).
- Qualitrol: For cable sections, a maximum of approximately 50 km between measurement points is recommended due to higher attenuation in cables.

(b) Limitations Regarding Remote In-Feeds

Unlike conventional impedance-based methods, TWFL technologies are largely unaffected by remote in-feeds. The inputs provided by different OEMS w.r.t. Remote-in-Feeds are as follows:

- On-line TWFL (GE Vernova): Completely independent of system parameters including in-feed/out-feed, as fault location is computed from GPS-synchronized timestamps alone.
- Off-line TWFL (Megger): Remote in-feeds have minimal impact as measurements are performed on de-energized lines.
- Off-line TWFL (Taurus-MKS): Since the system operates on a de-energized line, the influence of remote in-feeds is completely eliminated.

(c) Limitations Regarding Intervening Joints / Jumpers

The inputs provided by different OEMS w.r.t. Intervening Joints / Jumpers are as follows:

- GE Vernova: Mixed lines with different propagation constants require precise configuration of propagation constant (K) values for each section in the DR Manager software.
- Megger: Cable joints, transition points, and impedance discontinuities generate additional reflected waves that may complicate wave interpretation; detailed line models and reference signatures are needed.
- Taurus-MKS: Intervening jumpers, taps, repairs, and joints generate identifiable reflections; AI-assisted diagnostic software distinguishes normal line features from fault-related reflections using baseline comparison.
- Qualitrol: Correct cable velocity factor must be configured. The System is capable for in two in-circuit teed lines. In a hybrid circuit where there is a combination of overhead line and underground cables, the travelling Wave System is limited to two junctions between overhead line and underground cable sections.

5.7 Applicability and Effectiveness on Long HVDC Transmission Lines

India operates several major High Voltage Direct Current (HVDC) transmission links, including the 800 kV HVDC systems which represent the highest voltage class of DC transmission infrastructure. The TC-TWFL Committee considered the applicability of TWFL technologies specifically to these systems.

(a) On-line TWFL on HVDC Lines

The RPV311/RA333 architecture of GE Vernova is fully optimized for HVDC applications. The 5 MHz sampling rate is designed to detect the extremely fast transients characteristic of HVDC transmission. GE Vernova TWFL systems have been deployed in HVDC applications globally, including a 2,411 km, 600 kV DC Porto Velho-Araraquara HVDC line in Brazil.

Similarly, Qualitrol has submitted that their System can be applied to HVDC transmission Line.

(b) Off-line TWFL on HVDC Lines

Taurus-MKS Systems has confirmed that travelling wave principles are independent of AC or DC operating mode, making Off-line TWFL applicable to both HVAC and HVDC systems. The

technology has been successfully deployed and utilized on the following major Indian HVDC projects:

- Talcher-Kolar HVDC Link
- Agra HVDC System
- Pugalur HVDC System
- Kurukshetra HVDC System (over 15 years of deployment)

Additionally, the technology has been deployed on the BMTE transmission network in Brazil, including corridors up to approximately 2,544 km through the Amazon region. Long HVDC corridors exhibit lower attenuation and fewer intermediate discontinuities compared to AC networks, which is advantageous for travelling wave analysis. Factors such as smoothing reactors, line terminations, filters, and converter station interfaces may influence travelling wave behavior and should be considered during system configuration.

Megger's TWFL solution is an Off-line testing and fault location technology and is not intended for continuous On-line travelling-wave monitoring of energized HVDC transmission systems. Therefore, its applicability and effectiveness for On-line fault location on long ±800 kV HVDC transmission lines are not established. The system is primarily designed for Off-line diagnostics and fault location of de-energized overhead lines and cable systems.

5.8 Effectiveness on Mixed Overhead and Underground Cable Configurations

Mixed overhead-line/underground-cable configurations present greater challenges than homogeneous overhead transmission lines. The principal reasons are:

- different travelling-wave propagation velocities;
- different characteristic impedances;
- frequency-dependent attenuation;
- reflections at overhead/cable transition points;
- reflections at cable joints;
- termination effects; and
- sheath/bonding arrangements.

The Committee specifically recognized these challenges and observed that proper line modelling and configuration are essential. Various Inputs provided by OEMs w.r.t. effectiveness on Mixed Overhead and Underground Cable Configurations are as follows:

GE Vernova: GE Vernova indicated that its software can define different propagation characteristics for different line sections. The technology was stated to be applicable to hybrid lines, subject to proper configuration.

Megger: Megger stated that its technology is applicable to overhead lines and underground cable systems and therefore can be applied to mixed networks. However, location accuracy may depend on the complexity of the network topology and the availability of detailed line and cable data.

Qualitrol: Qualitrol stated that its TWFL system can be used for cable and hybrid overhead/cable circuits. However, it recommends a maximum cable-section length of approximately 50 km between measurement points, beyond which attenuation of high-

frequency travelling-wave components can make automatic detection more difficult. Qualitrol infomred that present technology is limited to approximately two junctions between overhead and underground cable sections for reliable operation.

Taurus-MKS: Taurus-MKS adopts a more application-specific approach. In mixed networks, the overhead-line and underground-cable sections may be treated as separate diagnostic entities, with dedicated cable fault-location equipment used for the cable section.

The Committee notes that complex cable networks may require specialized or separate fault location solutions rather than a single TWFL arrangement.

5.9 TWFL Products Ability to Use Existing Substation GPS

GPS/time synchronization is important primarily for double-ended On-line TWFL systems. The Time Synchronization requirement of different OEMs is given in the **Table-9**.

OEM	Type	GPS / Time Synchronization Requirement
GE Vernova	On-line	Requires IRIG-B (004 even parity) standard with sub-100 nanosecond jitter performance. Existing substation GPS CAN be utilized provided it conforms to IRIG-B standard and has spare output ports meeting the nanosecond-level jitter performance. Generally, uses GPS equipment with fibre optic output ports. TWFL devices also include inbuilt GPS as standard.
Qualitrol	On-line	Uses its own internal GPS module to ensure 100 nanosecond accuracy. System cannot use existing substation GPS. The System must be deployed with its own dedicated GPS and antenna at each substation terminal.
Megger	Off-line	GPS synchronization NOT required for Off-line TDR-based operation. No dependency on GPS, communication channels, or satellite infrastructure.
Taurus-MKS	Off-line	GPS synchronization NOT required for fault location operation. System performs all measurements from a single end. If GPS is available in substation, it may optionally be utilized for event logging, test documentation, and asset management purposes only. No dependency on GPS for core measurement function.

Table 9: GPS and time synchronization requirements by OEM and technology type

The Committee noted that for Off-line TWFL, GPS synchronization is not required because the fault location is calculated from the round-trip travel time of the reflected pulse at the same terminal.

5.10 Space, Power Supply, and Other Requirements for Substation Deployment

(a) On-line TWFL

GE Vernova:
The GE Vernova equipment consists of:

- RT430 GPS receiver;
- RPV311 Central Processing Unit;
- RA333 acquisition unit; and

- DR Manager software.

The stated power requirements are:
- 100–250 V DC; or
- 110–240 V AC

The physical equipment comprises approximately:
- RPV311: 3U, 19-inch rack;
- RA333: 5U, half-19-inch width.

The stated operating temperature ranges are approximately -10°C to +50°C for RPV311 and -40°C to +55°C for RA333.

The System can use existing station DC supply, with DC preferred, and normally does not require a separate UPS arrangement.

In addition to physical equipment, an On-line double-ended system requires:
- Equipment at both line terminals;
- Communication path;
- Time synchronization;
- Configuration database;
- Suitable interfacing;
- Secure station network; and
- Engineering/configuration support.

Qualitrol

The travelling wave system comes in a 3U high 19 inch rack chassis.

(b) Off-line TWFL

Taurus-MKS

Off-line systems have substantially lower permanent infrastructure requirements. Taurus-MKS supplies a portable system in rugged carrying cases and the system can be moved between line bays. It does not require permanent control-room installation, dedicated communication, remote-end equipment or GPS synchronization. The unit is battery operated and can conduct approximately 5–6 line tests per charge.

The principal requirements are:
- access to the line terminal;
- safe line isolation;
- proper grounding;
- suitable connection accessories;
- trained operating personnel; and
- battery charging facility.

Megger
- Mains Supply: 230 V ±10%, 49–61 Hz, ≤70 VA.

- Off-line/ Portable Device -deployed at substation. Whenever fault occurs during that time the kit is used.
- Thus, the TWFL product is a portable Off-line diagnostic system that can be deployed on demand at substations without requiring dedicated infrastructure or continuous power backup arrangements.

  Thus, from the infrastructure perspective, Off-line TWFL has a significant advantage where a single portable unit is intended to serve several transmission lines.

5.11 Consistency of Measurements

For On-line systems, configuration management is particularly important. Changes in line topology, line parameters, addition of bays or conversion of overhead sections to cable sections should be reflected in the TWFL configuration database. However, if correctly configured with site-specific line parameters, the system provides consistent and reliable fault location results.

In case of Off-line TWFL, the OEM responses indicate that TWFL systems provide repeatable measurements when properly configured. Megger stated that its system provides repeatable and consistent measurements when the test setup, line parameters and operating conditions remain unchanged. Taurus-MKS reported highly repeatable results under repeated testing of the same transmission line under similar conditions. It also stated that laboratory tests involving thousands of triggers demonstrated repeatability. Minor variations may arise because of changes in moisture, contamination, vegetation contact or temporary line conditions.

The principal factors affecting repeatability are therefore:

- accuracy of line parameters;
- propagation velocity;
- equipment calibration;
- connection arrangement;
- grounding;
- electromagnetic noise;
- changes in line configuration; and
- changes in physical/environmental line conditions.

5.12 Effect of improper grounding or incorrect equipment connection during actual usage

Correct grounding and connection are essential, particularly for Off-line systems involving high-voltage pulse injection.

Megger's system incorporates ground-loop detection and safety interlocks. If improper grounding or incorrect connection is detected, pulse injection is inhibited and an alarm/indication is provided to the operator.

Taurus-MKS provides two independent high-current-capacity 10 mm^2 copper grounding cables. The system also incorporates internal grounding verification, which checks the grounding condition before testing. If inadequate grounding is detected, the operator is alerted before the test is initiated.

Improper grounding may otherwise result in:

- measurement errors;
- nuisance triggering;
- unreliable travelling-wave detection; or
- unsafe operating conditions.

The Committee also recorded utility feedback that grounding can become particularly difficult during rainy conditions, potentially increasing testing time. Accordingly, grounding verification and electrical safety interlocks should be mandatory requirements in the technical specification for Off-line TWFL systems.

5.13 Normal expected life span of the TWFL product

The OEM responses w.r.t. normal expected life span has been shown in **Table-10.**

OEM / Product	Type	Expected Lifespan	Maintenance Requirements
GE Vernova	On-line	>20 years	Standard preventive maintenance; software updates; firmware upgrades as recommended by OEM. Operating within specified temperature and power ranges.
Qualitrol	On-line	15 years	Periodic inspection, calibration, and software updates.
Megger	Off-line	8-12 years	Periodic calibration and preventive maintenance as per OEM schedule. Battery replacement as required.
Taurus-MKS	Off-line	>15 years	Normal usage with periodic calibration and routine preventive maintenance. Product has been in continuous use since 1990. Annual AMC, calibration, and 24x7 technical support available. Annual training provided.

Table 10: Expected lifespan and maintenance requirements for TWFL products

5.14 Integration of Different-Make Relays

On-line TWFL should preferably be manufacturer-agnostic with respect to the protection relays installed at the two ends of the line. The OEMs response indicate that TWFL can be manufacturer-agnostic, while interoperability depends on:

- communication architecture;
- data-exchange protocols;
- time synchronization;
- TWFL acquisition-system compatibility; and
- appropriate configuration/mapping of measurements.

Therefore, the use of different relay manufacturers at the two ends should not by itself constitute a barrier to implementation of On-line TWFL. However, the TWFL system should not depend unnecessarily on proprietary relay hardware or proprietary communication protocols. The technical specification should require the TWFL system to interface with

protection systems through open/standardized interfaces and to remain functional even where Main-1 and Main-2 relays are of different makes.

A key requirement for On-line TWFL deployment in Indian substations, where protection relays of multiple makes may be installed especially at the two ends of the line, is that the TWFL system should be compatible with relays from different manufacturers. In this respect inputs provided by OEMs are given as below:

- GE Vernova (On-line TWFL): The system is manufacturer-agnostic with respect to protection relays.
- Qualitrol (On-line TWFL): Protection relay type has no bearing on Qualitrol's Travelling Wave solution.
- Megger and Taurus-MKS (Off-line TWFL): Off-line systems do not interact with protection relays, synchronized measurements, or communication links. Issues of relay make compatibility are therefore not applicable in case of Off-line TWFL.

An important operational consideration noted by the Committee is that proper configuration management is necessary when using On-line TWFL. Any change in line topology, addition of a new line or bay, modification of line parameters, or change from overhead to cable sections would require corresponding updates to the TWFL system database and configuration. This must be managed as part of the substation asset management process.

5.15 Future developmental efforts w.r.t. Integrating the TWFL product with the Protection Relays

The TC-TWFL Committee examined the prospects for future integration of TWFL functionality directly into protection relays. OEM-specific development roadmaps are as follows:

GE Vernova:

GE Vernova acknowledges the fundamental challenge of the sampling rate mismatch as relays sample at 4–16 kHz, while TWFL requires 1–5 MHz to capture high-frequency transients.

Qualitrol:

Qualitrol reported development of a software solution called Grid Assist, intended to integrate protection-relay fault records with Qualitrol's Travelling Wave fault location system data and present combined information on a map-based application for fast and easy review.

Taurus-MKS:

Taurus-MKS has proposed integration of the proven Off-line TWFL technology with an On-line Continuous Transmission Line Monitoring and Health Monitoring System. A Proof of Concept (POC) was successfully demonstrated in 2016 in collaboration with PGCIL at Maithon Substation, on 220 kV and 400 kV transmission lines. The POC validated continuous online transmission line monitoring, health assessment, travelling-wave-based monitoring, fault detection, line signature acquisition, and identification of line abnormalities under live operating conditions. The proposed online monitoring system operates by continuously injecting controlled travelling-wave pulses through the PLCC (Power Line Carrier Communication) channel, enabling fault and transmission line abnormality detection within

approximately 2 to 3 milliseconds of occurrence. Taurus-MKS expressed willingness to further conduct a detailed POC demonstration.

Megger:

Megger's TWFL solution is an Off-line, portable fault location and diagnostic system and does not require integration with protection relays for its intended operation.

5.16 Effectiveness of On-line/ Off-line TWFL technologies for subsea cables

Subsea cable fault location represents a specialized and technically demanding application of TWFL technologies. The TC-TWFL Committee obtained OEM positions on this aspect which has been summarized below:

Technical Challenges Specific to Subsea Cables:

- Greater cable length compared to typical land-based installations.
- Higher cable capacitance, leading to greater signal attenuation and dispersion.
- Travelling wave propagation velocity in cables is significantly lower than overhead lines (typically 45-60% of overhead-line velocity), requiring correct velocity factor configuration.
- Cable joints; Sheath/ Bonding effects; and potentially very long cable sections affect the fault detection in Subsea Cable
- Fault pinpointing in subsea environment requires Remotely Operated Vehicles (ROVs) or specialized underwater equipment, which is fundamentally more complex than land-based fault location.
- High discharge requirements necessitate specialized high-power test equipment.

The Committee notes that subsea cable TWFL applications are significantly more complex than land-based transmission line applications, and all OEMs acknowledge that specialized equipment configurations and methodologies are required.

Megger: Megger reported experience on a 761 km subsea cable project connecting the UK and Denmark and indicated that specialized equipment/configuration is required for subsea applications. Challenges include longer cable length, higher cable capacitance, high discharge requirements, subsea pinpointing and the need for suitable pre-location techniques.

Qualitrol: Qualitrol stated that its TWFL system can be used on cable circuits and hybrid overhead/cable circuits. However, based on cable attenuation characteristics, it generally recommends approximately 50 km maximum cable-section length between measurement points for reliable automatic detection.

Taurus-MKS: Subsea cables require specialized approaches due to different electrical characteristics, propagation behaviour, attenuation, and reflection properties. Subsea cable systems are a specialized application area requiring further optimization. Taurus-MKS is willing to conduct studies and validation on suitable subsea cable installations.

6. Guidelines/ Recommendations for TWFL Technology

The Committee for preparation of Guidelines/ Procedure for implementation of Travelling Wave Fault Locator (TWFL) on critical transmission lines, examined the subject in a comprehensive manner through their meetings, technical presentations by OEMs, and responses to technical and operational queries raised to OEMs with respect to different TWFL technologies. The Committee considered both On-line and Off-line TWFL solutions, including their operating principles, system configuration, fault-location methodology, accuracy, applicability to different transmission line configurations, communication and synchronization requirements, integration with existing protection and substation systems, auxiliary power and space requirements, availability, manufacturing and deployment capability, Make in India aspect, cost, manpower requirements, operational suitability and scalability.

The Committee has observed that even though off-line TWFL is a more economical solution compared to on-line TWFL, the latter may still be preferred for highly important transmission corridors where rapid restoration of lines by automatic identification of fault locations is required for grid security. Off-line TWFL are more suitable where portability, multi-line utilization, diagnostic applications and lower infrastructure requirements are important considerations.

For finalizing the TWFL Guidelines w.r.t. HVDC and 400 kV & above systems, the Committee has considered the CEA Guidelines dated 11.05.2025 on Standard Operating Procedure for Restoration of Transmission System, which inter-alia, provides the criteria for identifying a substation as critical, and has concluded that those would be the ideal locations for providing Off-line TWFL Devices.

W.r.t. 220 (230) kV Network, the Committee observed that 220 kV lines exceeding 200 km are comparatively few in number in most parts of the country; hence, adopting 200 km line length as a general screening criterion would primarily identify unusually long 220 (230) kV lines where physical fault patrolling may be difficult and restoration time may be comparatively high. As such, a general criterion of 200 km line length could be considered for deployment of Off-line TWFL Devices. However, in locations where the lines pass through hilly, forested or otherwise difficult terrain, a lower threshold of approximately 100 km may be considered. This criterion of 200 km/ 100 km would be valid across all regions of India including North Eastern Region.

Considering the North-Eastern Region's distinct transmission network, difficult terrain and accessibility constraints, the Committee has agreed that there may be a need for providing Off-line TWFL Devices in its 132 kV transmission network also. After thorough deliberations, the Committee has decided to adopt 100 km as the minimum threshold for line length for stations in normal terrain and 50 km as the minimum threshold for line length for stations in difficult or hilly terrains for providing Off-line TWFL Devices in North Eastern Region.

After detailed deliberations, the following Guidelines/ Procedure have been formulated for implementation of TWFL across the country, covering both Inter-State Transmission System (ISTS) and Intra-State Transmission System, with due consideration to region-specific, system-specific and line-specific requirements.

6.1 Guidelines for Mandatorily Providing Off-line TWFL Devices

1. <u>400 kV & Above Stations [applicable across all Regions in India]:</u>

(a) All 765 kV stations
(b) All Stations at Voltage level 400 kV and above where Inter-Regional lines terminate or are important for import of power by any specific state
(c) All Stations which handle more than 3000 MW of power capacity
(d) All or selected Stations at 400 kV and above voltage level which are essential to ensure continuity of supply to following category of loads as per information furnished by State Load Despatch Centre and DISCOMs:
    (i) State Capitals
    (ii) Railways, metro rail, airports, refineries, underground mines, defence establishments. VIP areas, Space, ports and important industries.
    (iii) Important for islanding scheme of nuclear power plants or major metropolitan areas or defence establishments

2. <u>220 kV (230 kV) Stations [applicable across all Regions in India]:</u>

(a) All Stations in normal terrain having any lines with line length of more than 200 km
(b) All Stations in difficult or hilly terrain having any lines with line length of more than 100 km

3. <u>132 kV Stations (applicable only to North-Eastern Region):</u>

(a) All Stations in normal terrain having any lines with line length more than 100 km
(b) All Stations in difficult or hilly terrain having any lines with line length more than 50 km and susceptible to frequent tripping due to vegetation and/ or bamboo encroachment.

6.2 Guidelines for Mandatorily Providing On-line TWFL Devices:

On-line TWFL Devices shall be **mandatorily** provided on all HVDC Transmission lines. For remaining applicable cases, the concerned Utilities may decide upon providing the same (**hence optional**) in the following order of priority:

(a) All 765 kV and above transmission lines
(b) 400 kV and above transmission lines having average loading of more than 1500 MW or any higher threshold as deemed appropriate by the utility.

6.3 General Guidelines to be followed for TWFL

Along with the deployment of TWFL Technology in accordance with the guidelines/procedures specified in this Report, utilities shall ensure the following:

(a) TWFL should be deployed as an additional fault-location and diagnostic layer and should complement, and not replace, the primary protection system.

(b) In case of deployment of On-line TWFL Technology, only Double-Ended TWFL Technology shall be utilized. Single-Ended TWFL Technology shall not be considered for On-line TWFL applications.

(c) For On-line TWFL applications, accurate and reliable time synchronization should be ensured and periodically verified to maintain the required accuracy of fault-location estimation. Existing station GPS/ Time-synchronization infrastructure should be utilized wherever technically compatible and suitable for TWFL application.

(d) TWFL systems should be designed to operate independently of the make/ manufacturer of the existing protection relay.

(e) For Double-Ended On-line TWFL systems, secure and dedicated communication channels should be preferred to ensure reliable transmission of travelling-wave data and fault-location information. In no case public network shall be used for communication purpose.

(f) Cybersecurity provisions, availability of critical spares, calibration facilities, after-sales technical support and long-term maintainability should form an integral part of the procurement evaluation.

(g) Adequate provision should be made for critical spares, training of operating and maintenance personnel, Annual Maintenance Contracts (AMC), technical support and future software and firmware upgrades throughout the intended service life of the system.

(h) Applications involving mixed overhead line-cable sections and subsea cables should be subjected to project-specific technical evaluation, considering the effects of propagation velocity, attenuation, impedance discontinuities and associated reflections on TWFL performance.

(i) Periodic review of the deployed TWFL systems should be undertaken, with provision for incorporating future developments in high-speed data acquisition, protection-relay integration, line-health monitoring and AI-assisted travelling-wave analysis, as technically and operationally appropriate.

(j) Proper grounding/ earthing arrangements and necessary safety interlocks should be provided to ensure safe and reliable operation and maintenance of the TWFL system.

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