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Webinar Nº 02:

Voltage, Reactive Power & FACTS for High-VRE Grids

- Cambodia
- Tajikistan
- Uzbekistan

Before We Start

Interpretation
You may select your language preference — English–Russian simultaneous interpretation is available.

Q&A
You may submit your questions at any time; our speakers will respond during the webinar.

Slides
The slides and a short technical note will be shared after the session.

Recording
This session is being recorded for project documentation purposes.

90
MINUTES

- Voltage, reactive power and system strength under high VRE
- FACTS and dynamic reactive technologies
- Stability in weak, inverter-dominated grids, with real-world cases
- Moderated discussion and Q&A

RUNNING ORDER

The Plan for Today

1	**Welcome and framing**	Atsumasa Sakai — ADB · Gökhan Tosun — MRC Türkiye
2	**The constraint: voltage, reactive power, strength**	Mevlüt Akdeniz — HLT Expert, MRC Türkiye
3	**The toolbox: FACTS and dynamic reactive plant**	Müfit Altın — Solutions Architect
4	**Weak, inverter-dominated grids — real cases**	Gilles Chaspierre — Dynamics & Stability Expert
5	**Moderated discussion and live Q&A**	All speakers · Moderator: Gökhan Tosun
6	**Synthesis, next steps and closing**	Gökhan Tosun — MRC · Atsumasa Sakai — ADB

SECTION 1

Welcome and Why This Matters

Atsumasa Sakai · Senior Energy Specialist, ADB
Gökhan Tosun · Project Director, MRC Türkiye

THE ROADMAP

Where Today Fits

MAY

Webinar 1

The full menu of high-level technologies, and how we screen them

21–22 MAY

Inception Workshop

Tashkent — systems, priorities and your topic rankings

TODAY

Webinar 2

Your top-ranked topic: voltage, reactive power, FACTS

NEXT

Webinar 3

Number two on your list: flexibility, forecasting, reserves – *To be determined*

HOW WE WORK

The One Habit

Start with the problem, not the technology.

Constraint

What is actually binding? Measure it.

Service

VARs, fault current, damping — which one?

Technology

Which device delivers it best?

Evidence

Prove it with a study and a number.

Constraint → Service → Technology → Evidence

THE HLT FRAMEWORK

Five Technology Pillars

1	Frequency, inertia and system strength	WEBINAR 1
2	**Voltage, reactive power and transfer**	**TODAY**
3	Interconnection and regional control	CONTEXTUAL
4	Monitoring, protection and resilience	PARTLY TODAY
5	Forecasting and flexibility	WEBINAR 3

01 Poll

Where does your system stand today?

QUESTION 1

High voltage at light load, low voltage at peak, both, power quality — or not established yet?

QUESTION 2

Is reactive power reserve or voltage margin available to control-room operators in real time?

SECTION 2

The Constraint: Voltage, Reactive Power & System Strength

Mevlüt Akdeniz · High-Level Technology (HLT) Expert, MRC Türkiye

THE SHIFT

What Actually Changed

A grid built on machines

Voltage held up by spinning machines

Reactive reserve, big and automatic

Strong fault current everywhere

Collapse was slow, and rare

A grid built on inverters

Voltage stiffness fades as machines retire

Reactive power only if we configure it

Fault current drops at the edges

New failures: fast, and control-driven

THE LINE THAT MATTERS MOST

Capability is not contribution.

A datasheet says what a device can do. An event shows what it actually does.

Capability

The reactive range printed on the datasheet

Contribution

What it really delivers when voltage moves

The gap

Wrong mode, slow switching, bad settings — nothing happens

DIAGNOSTIC 1

The P–V Curve — Know Where the Edge Is

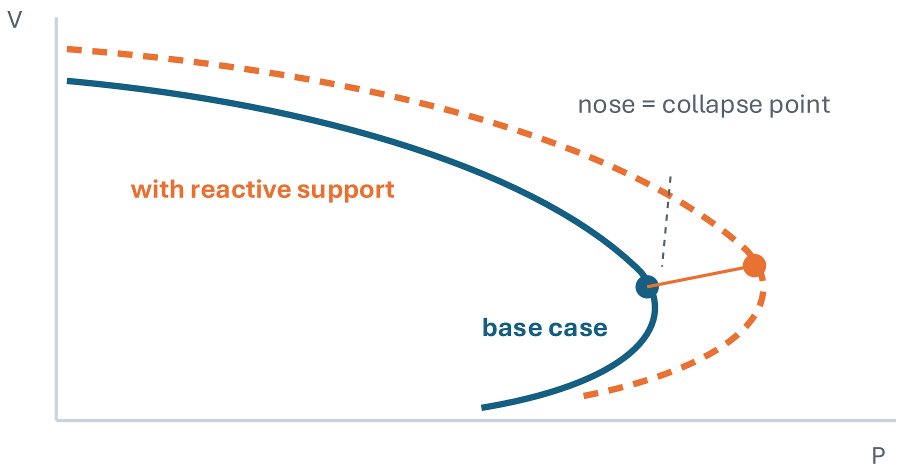
HOW TO READ IT

Push more power, voltage sags

The nose is the cliff edge

Margin = distance to the nose

Add VARs, the nose lifts



Schematic. The knee is where a small extra load collapses the voltage.

DIAGNOSTIC 2

The Q–V Curve — How Many Mvar to the Cliff

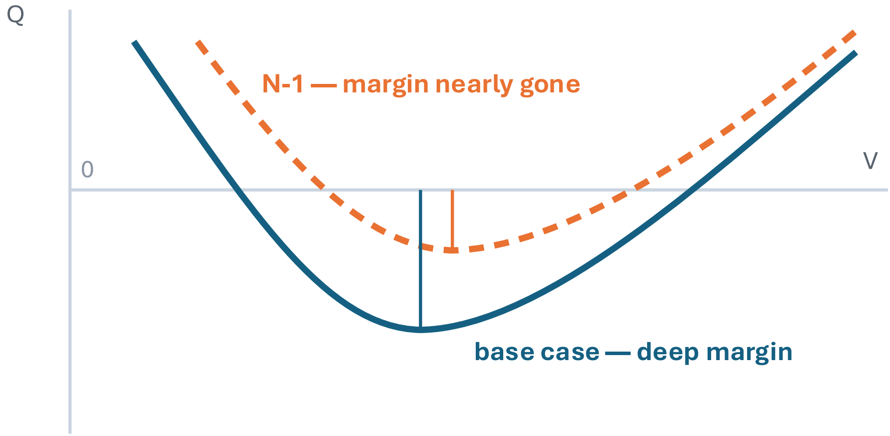
HOW TO READ IT

Inject VARs, voltage rises

Curve bottom = collapse point

Depth below zero = Mvar margin

N-1 eats most of the margin



Illustrative Q–V curves at a weak bus. The N-1 case, not the base case, sets the STATCOM size.

THE REQUIREMENT

The Two-Sided Problem

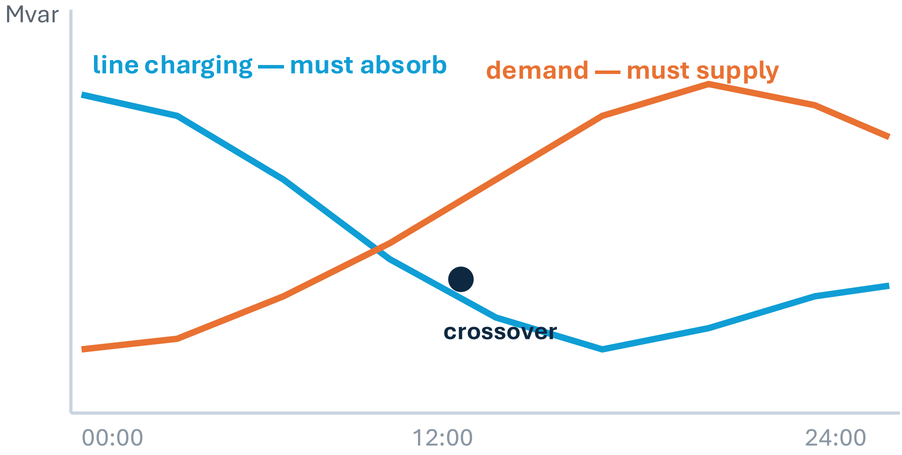
THE CATCH

Night: surplus, voltage climbs

Peak: deficit, voltage sags

The system must absorb *and* supply

Fixed banks fix half the day



Illustrative. Charging dominates at night; absorption need falls away at peak. The curves cross mid-day.

FIDVR

The Motor Trap

1

Voltage dips

A fault pulls voltage down for a fraction of a second

2

Motors stall

Stalled induction motors pull huge reactive current

3

Voltage stuck low

That current holds voltage down after the fault clears

4

Cascade risk

Undervoltage protection starts tripping load and plant

The cure is fast VARs — a STATCOM holds current at low voltage, where a capacitor gives up.

SYSTEM STRENGTH, IN PLAIN TERMS

A strong grid holds its voltage when current is injected. A weak one does not.

Short-circuit ratio measures that stiffness — and it falls as machines retire.

High ratio

Stiff voltage — inverters behave

Low ratio

The plant moves its own voltage — trouble

Falling fast

Worst exactly where new solar connects

ONE HIERARCHY, NOT FIVE DEVICES

Voltage Control — Roles and Coordination

ASSET	FUNCTION	COORDINATION RULE	WATCH
Generator AVR	Local regulation	Must not fight the fast devices	Voltage, Mvar output
STATCOM / SVC	Fast dynamic support	Leads — takes priority over tap changers	Response time, Mvar
Inverter plants	Reactive injection	Stay inside the grid-code envelope	Verified response
Tap changer	Normalisation	Slow and last — avoid hunting	Taps per hour
Shunt devices	Static support	Scheduled with the dynamic devices	Switching frequency

UZBEKISTAN

Two Problems, One Grid

High in the west at night. Low in Fergana at peak. Fixed devices cannot serve both.

▲ **West — Samarkand, Bukhara, Navoi**
Charging surplus — runs high overnight

▲ **Tashkent cascade**
Generation-dense, high at light load

▼ **Fergana valley**
Reactive-short, imports, sags at peak

▲▼ **Karakalpakstan / Khorezm**
Swings both ways — the weakest nodes

TAJIKISTAN

A Summer, Pumping Problem

Long southern feeders, heavy irrigation load, low voltage in summer.

▼ **Vakhsh and Khatlon feeders**
Irrigation pumping — undervoltage, FIDVR

Q **TALCO smelter, Tursunzoda**
Large industrial reactive and harmonic load

N-1 **North–South 500 kV corridor**
One long backbone, N-1 exposed

90% **Hydro-dominated — inertia is fine**
Machines are plentiful; the Uzbek recipe does not transfer

CAMBODIA

Long Wires, One Load Centre

Solar is arriving faster than the strength to host it.

Phnom Penh ring
Receiving end of long corridors — soft buses

SCR **Pursat / Kampong Chhnang**
Solar-plus-storage cluster, low strength

NE and SW hydro corridors
Long evacuation, tight in the dry season

? **Rooftop and distributed solar**
Growing — and invisible to the operator

CAPS — THE REGIONAL DIMENSION

Voltage is local. The Central Asian ring shares the consequences.

A reactive problem at an interface bus becomes a neighbour's problem within seconds.

UZ–TJ interfaces

Transfer limited by voltage, not heat, at peak

Reactive at the border

Unplanned VAR exchange loads the ties

Shared reserves

One weak corridor sets the ring's N-1 limit

CDC Energiya's seat

Coordinated voltage schedules and data exchange

02 Poll

System Conditions and Readiness

WHICH SYMPTOMS

What warning signs does your control room actually see?

WHICH REGION

Where is your greatest area of concern?

Key Takeaways

01 Capability is not contribution. A datasheet does not hold voltage — control mode does.

02 The requirement is two-sided: absorb at night, support at peak. Variable, not fixed.

03 Measure before you procure: rank the weak buses, size the support, verify the recovery.

04 Three systems, three distinct requirements. A single template will not fit all.

SECTION 3

The Toolbox: FACTS and Reactive Technologies

Müfit Altın · Solutions Architect

THE SELECTION TABLE

Matching Constraints to Technologies

BINDING CONSTRAINT	SERVICE NEEDED	TECHNOLOGY
High voltage at light load	Reactive absorption	Reactors, MCR, STATCOM / SVC
Low voltage at peak	Reactive supply	Capacitors, then SVC / STATCOM
Slow fault recovery (FIDVR)	Fast VARs at low voltage	STATCOM, condenser
Not enough transfer	Flow or impedance control	Series compensation, PST, FACTS
Weak grid, low SCR	Fault current and stiffness	condenser, grid-forming
No operational visibility	Real-time margin	Online monitoring inside the EMS

THE PASS–FAIL TEST

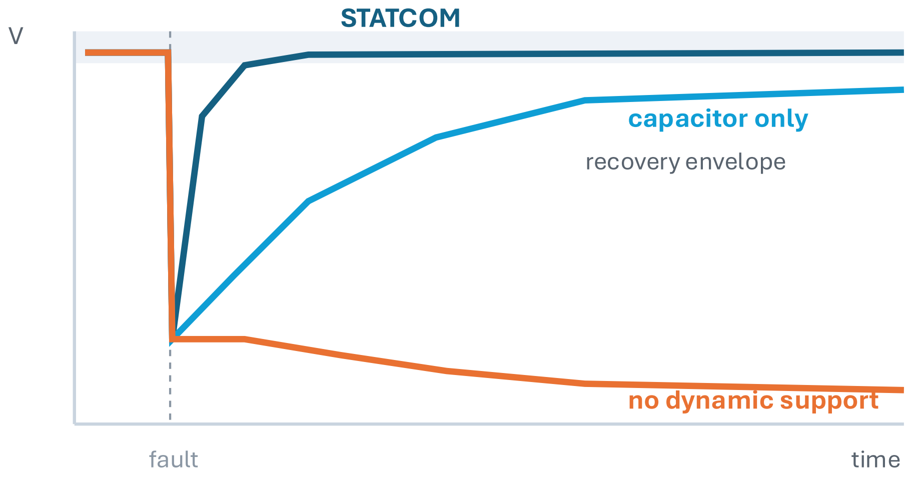
Voltage Recovery — Why the Fast Device Wins

SAME FAULT, THREE PORTFOLIOS

STATCOM — back in ~0.4 s

Capacitor — output ∝ V^2, slow, FIDVR risk

Nothing — motors stall, then trips



Illustrative RMS response on a motor-heavy feeder. The recovery envelope is the acceptance criterion.

HLT 9

STATCOM

voltage-source converter

RESPONSE	RANGE	AT LOW VOLTAGE	FOOTPRINT
< 1 cycle	**±50–300 Mvar**	**holds current**	**compact**

WHAT IT DOES

A controlled current source, not a capacitor

Holds rated current down to low voltage

Symmetric ± VARs, with short-term overload

WHERE IT FITS

Weak buses and renewable-corridor interfaces

FIDVR-prone, motor-dense areas

HVDC terminals; steadies nearby inverters

SPECIFY IT RIGHT

Recovery time and fault-current injection

Behaviour at the current limit; harmonics

Availability KPIs; EMS setpoints and flags

In service: Terna (IT) with a defence plan · EirGrid (IE) TSO-grade specification

HLT 10 SVC thyristor-controlled reactor and capacitors

RESPONSE	RANGE	AT LOW VOLTAGE	COST
20–40 ms	**large, often ±**	**fades ($\propto V^2$)**	**below STATCOM**

WHAT IT DOES

Continuously variable across a large range

Mature and robust — decades in service

Filters come with useful Mvar

WHERE IT FITS

Where a big VAR range beats low-voltage depth

Steady reserve on long corridors

Holding voltage on a constrained interface

SPECIFY IT RIGHT

Prove the benefit with and without — do not oversize

Harmonic filter design up front

Tune gains against STATCOMs and AVRs

In service: Widely deployed worldwide, often paired with existing filter banks

HLT 16
Shunt Reactors & MCR

SWITCHED	MCR	JOB	COST
0.1–5 s	0.3–1 s	absorb VARs	lowest to absorb

WHAT IT DOES

A fixed or switchable reactor absorbs reactive power

MCR absorbs continuously, not in steps

Attacks light-load overvoltage directly

WHERE IT FITS

Long, lightly-loaded lines and cables

Uzbekistan's western reactive surplus

The first move, before any power electronics

SPECIFY IT RIGHT

Automate switching — pre-set control schemes

Enough steps, or go variable (MCR)

Coordinate with the dynamic devices

In service: Standard on long EHV lines; MCR where the surplus varies through the day

HLT 5

Condenser

FAULT CURRENT	INERTIA	AVR	FOOTPRINT
3–6 × rated	**H ≈ 1–2 s**	**~150 ms**	**large, rotating**

WHAT IT DOES

A machine with no prime mover

Reactive power, real inertia *and* fault current

The only device here that helps protection

WHERE IT FITS

Low-SCR clusters where inverters wobble

Where falling fault levels break protection

Cambodia's weak solar clusters — a real candidate

SPECIFY IT RIGHT

Site it from the short-circuit study

Consider repurposing a retired unit

Plan starting, cooling and rotating maintenance

In service: AEMO / South Australia for system strength · National Grid (GB)

HLT 12

Series Compensation

COMPENSATION	EFFECT	RISK	COST
30–70%	−X, + transfer	SSR / SSCI	low per MW

WHAT IT DOES

A series capacitor cancels part of the line reactance

Raises transfer and lifts the voltage profile

The cheapest way to uprate a long corridor

WHERE IT FITS

Long corridors where transfer, not heat, binds

Western Uzbek and North–South Tajik lines

When new right-of-way is impossible

SPECIFY IT RIGHT

Study sub resonance in the base design

Redesign distance protection for the reach change

MOV and bypass — treat it as a specialist asset

In service: Svenska kraftnät (SE) — new 400 kV series compensation

HLT 11

FACTS and Phase-Shifters

PST	TCSC	UPFC	SPEED
phase angle	**variable X, fast**	**V + angle**	**seconds / ms**

WHAT IT DOES

Controls impedance, angle or voltage to route power

PST is the workhorse for loop and interface flows

TCSC adds fast control and damps oscillations

WHERE IT FITS

Meshed interfaces with loop flows

Pushing power off a congested corridor

More transfer out of existing assets

SPECIFY IT RIGHT

Compare fairly against reinforcement, DLR, HVDC

Coordinate with PSS, HVDC and inverter controls

TCSC changes protection reach — update it

In service: Swissgrid and TenneT for PST loop-flow control · RTE

HLT 13 · 14

HTLS and Dynamic Line Rating

HTLS TEMP	HTLS GAIN	DLR GAIN	DLR COST
150–210 °C	+50–100%	+10–30%	very low

WHAT IT DOES

HTLS reconductors the same towers, runs hotter

DLR rates the line on real weather, not worst case

Both unlock capacity with no new right-of-way

WHERE IT FITS

Thermally-limited corridors, everywhere

Cambodia's long evacuation paths

Before you consider a new line

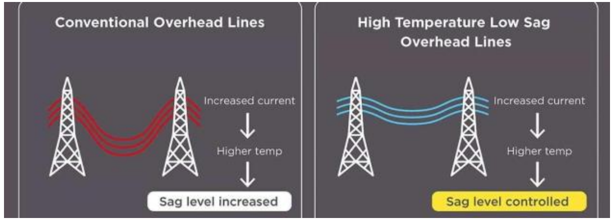
SPECIFY IT RIGHT

HTLS: clearances, fittings, substation ratings

DLR: govern the data; set conservative fallbacks

Update EMS ratings and protection afterwards

In service: Elia (BE), National Grid (GB), RTE and TenneT run DLR live today



Conventional vs high-temperature low-sag conductor

HLT 15 Online Voltage-Stability Monitoring

SHOWS	ALSO	SPEED	COST
V–Q margin	reactive reserve	near real-time	lowest of all

WHAT IT DOES

Puts margin and collapse distance in the EMS

Turns an offline study into a live picture

Lets you manage on evidence, not caution

WHERE IT FITS

All three countries asked for this

Corridors derated today as a precaution

The foundation the other devices lean on

SPECIFY IT RIGHT

Feed it good state estimation and validated models

Map every alarm to a clear operator action

Tune thresholds on real events; flag bad data

In service: EirGrid, Swissgrid, Terna — with WAMS as the data backbone

ORDER OF MAGNITUDE ONLY

Cost, Footprint and Lead Time

DEVICE	COST	LEAD TIME	FOOTPRINT / NOTES
Switched shunt / reactor	**Lowest**	6–12 months	Small; mechanical, limited operations
Variable reactor / MCR	**Low–medium**	12–18 months	Moderate; continuous absorption
SVC	Medium	18–30 months	Large; filter and reactor yard
STATCOM	Higher per Mvar	18–30 months	Compact; converter building
condenser	**High**	24–36 months	Large, rotating — or repurpose a retired unit
Series compensation	Low per MW	24–36 months	Platform; SSR studies; protection redesign
HTLS / DLR	**Very low (DLR)**	6–18 months	Reconductor or sensors — the fastest wins

The cheap, fast wins sit at the top and bottom — do them while the big assets are still in procurement.

BEYOND PILLAR 2

When Inverters Become the Fix

1 A battery gives VARs too

Its four-quadrant inverter provides fast reactive power as a by-product — often a free voltage asset

2 Grid-forming is a voltage source

It sets voltage and angle, so it stiffens a weak grid the way a machine does — without the spinning mass

3 It is entering the codes

AEMO and the GB grid code now specify grid-forming behaviour; Cambodia's Pursat battery is already there

4 The catch

It needs headroom and good models — and it cannot provide sustained fault current like a condenser

03 Poll

Technology Priorities and Implementation Constraints

RANK

Rank the technology groups in order of priority

OWN

Which technology groups are currently in operation?

BLOCK

What is the principal implementation constraint?

SESSION 3

Key Takeaways

01 Specify the response — recovery time and low-voltage current, not a nameplate rating.

02 Start cheap, but know the limits. Capacitors fade at low voltage; that is the STATCOM's job.

03 Coordinate the devices — one hierarchy, with fast reactive support taking the lead.

04 Monitoring delivers the most value per unit cost. See the margin, then act on it.

SECTION 4

Stability in Weak, Inverter-Dominated Grids

Gilles Chaspierre · Power-System Dynamics & Stability Expert

SHORT-CIRCUIT RATIO

The number we all trust was only ever a proxy.

It measures fault current. What we care about is voltage stiffness.

It worked because

High fault current meant machines nearby — and machines mean stiffness

It breaks because

A grid-forming converter gives stiffness with almost no fault current

Two grids, same ratio

One oscillates within a year; the other runs clean

So

Same number, opposite reality. One figure is not enough

TWO KINDS OF INVERTER

Following vs Forming

Grid-following

most of the existing fleet

Follows the grid's voltage with a PLL

Behaves as a current source

In a weak grid, the PLL loses the plot

No inertia, tiny fault current, no black start

Grid-forming

Pursat is one of them

Sets its own voltage, follows nothing

Behaves as a voltage source, like a machine

Stays stable even at very low strength

Inertia-like response, supports restart

RMS IS NOT ENOUGH

Load-flow and RMS will not reveal a converter oscillation.

EMT is required — with vendor models that have been validated.

The gap

RMS cannot capture PLLs or fast control loops

The rule

Run EMT where strength is low or converters cluster

The catch

Generic models hide the risk — demand real ones

The test

Replay a real event. If it cannot be reproduced, it cannot be predicted

CONTROL OR PHYSICS

Two Routes to Strength

Grid-forming (E-)STATCOM

strength through control

Stiffness without fault current

Compact, static, fast, low maintenance

Limited fault current, bounded inertia

condenser

strength through physics

Real fault current for protection

Real inertia, for free

A retired machine can be repurposed

Iberian Peninsula Blackout — 28 April 2025

A voltage issue, start to finish: the sequence, the three root causes, the fixes.

12:33	84 s	2.5 GW+	12–16 h
Spain and Portugal go dark	From first sign to separation from Europe	Generation lost in the cascade, mostly inverters	To bring both systems back

This was a voltage event. Frequency only moved later, once the generation was already gone.

Source: ENTSO-E Expert Panel Final Report, 20 March 2026

PMU VOLTAGE AT CARMONA

The 84 Seconds

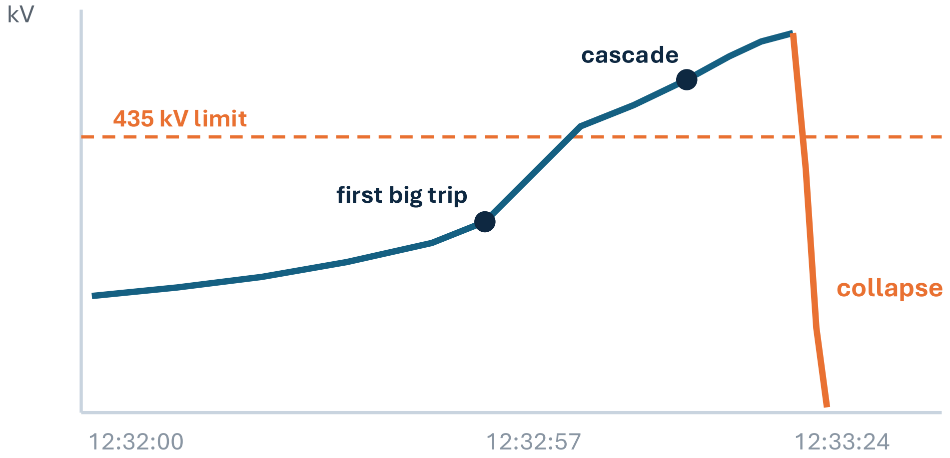
THE TRAJECTORY

Voltage rises, then rises faster

Straight through the 435 kV limit

Each trip pushes it higher

Then collapse



Reconstructed from the ENTSO-E Final Report. The climb is the whole story.

28 APRIL 2025

How the Collapse Unfolded

12:32:00

Voltage starts up

Plants drop output at fixed power factor, dragging VARs with them

12:32:57

First big trip

A transformer near Granada — 355 MW and its 165 Mvar sink gone

12:33:16

The cascade

727 MW near Badajoz, then 928 MW more in the south. Voltage runs away

12:33:24

Separation

Spain splits from Europe. The lights go out

THE CONDITIONS THAT SET IT UP

The Morning Before

That morning	Clear spring Monday — high solar and wind, low demand, few machines online
From 09:00	Voltage increasingly variable, close to the upper operating limit
Late morning	A forced 0.63 Hz oscillation, then a 0.2 Hz inter-area mode
~1 hour before	**Several reactors switched out manually to correct low voltage**
Pre-existing	Two border tie-lines already on planned outage

The reactive absorption they would soon need had been switched out an hour earlier — by hand.

ROOT CAUSE 1

Voltage Control Broke Down

1

Manual switching

Reactors switched by hand — too slow, some left out

2

Fixed power factor

Solar ignored voltage entirely. No help at all

3

Machines under-delivered

Conventional plants missed their VAR targets

4

No dynamic spec

No requirement, no penalty, no compliance check

5

Thin margins

Almost no room before plants disconnected

ROOT CAUSE 2

Spain had the reactive capacity. It could not switch it in fast enough.

The reactors were available; the switching was manual; the event lasted 84 seconds.

The finding

Substantial shunt-reactor capacity, available, never activated

Why

Manual action needed more time than the event gave

The lesson

Capacity that cannot be activated in time is not capacity

The fix

ENTSO-E now says: automate, and buy flexible devices

SO WHAT, FOR US

Implications for the Three Systems

Uzbekistan	This is what a night-overvoltage cascade looks like. Automate the reactors; check the settings
Tajikistan	Your problem is the opposite, but the control-mode question is identical. Fix it in the connection rules
Cambodia	The closest match: grid-following fleet, low strength, invisible rooftop PV — all three were central in Spain
All three	Three near-free actions: check control mode, check protection settings, time a reactor switch

CASE STUDY 2 · WEST MURRAY ZONE, AUSTRALIA

Retuned inverter controls, not new hardware, lifted the constraint.

The diagnosis

EMT studies found five plants' controls interacting at low SCR

The fix

Vendors retuned the inverters to work in concert; staged tests

The follow-through

System-strength remedies and tighter connection screening

The lesson

Demand real vendor models before you connect the cluster

SIX THINGS YOU CAN START THIS MONTH

Immediate Actions

1 Check the control mode

Voltage control or fixed power factor? Find out

2 Check protection settings

Against real withstand limits, with margin

3 Time a reactor switch

Decision to breaker — how many seconds?

4 Demand real models

Vendor-specific and validated, as a condition

5 Check strength first

Before the next cluster connects

6 Show the margin

On the operator's screen, tied to an action

Key Takeaways

01 Capability is not contribution. The capacity existed; mode, speed and settings blocked its use.

02 Do not rely on one indicator. Strength is stiffness — sensitivities, impedance scans, EMT.

03 Weak-grid failures live beyond the reach of RMS. Use EMT with validated models.

04 Protection settings are a system-wide matter. Margins that are too tight turn events into blackouts.

SECTION 5

Discussion and Priorities

All speakers · Moderator: Gökhan Tosun

DISCUSSION QUESTION 1 · OVER TO YOU

Which voltage and reactive-power constraints bind first in your system?

- **Voltage profile**
  High at light load or low at peak — and how is each managed today?
- **Transfer limits**
  Where do voltage limits bind before thermal limits?
- **Seasonal variation**
  How far does the reactive requirement move across the year?
- **Regional coordination**
  How is voltage support coordinated across interconnected systems?

DISCUSSION QUESTION 2 · OVER TO YOU

Four questions the Iberian event puts to every system operator.

- **Control mode**

  Voltage control or fixed power factor — and how is it verified?

- **Activation time**

  Manual or automatic — what is the actual activation time?

- **Operational visibility**

  Is reactive margin visible to operators in real time?

- **Protection settings**

  When were overvoltage and ride-through settings last reviewed?

YOUR QUESTIONS — ASK ANYONE

Open Floor

Mevlüt Akdeniz	Müfit Altın	Gilles Chaspierre	Gökhan Tosun
The problem — stability, margins, strength, diagnostics	The devices — choosing, specifying, sizing, siting, cost	Weak grids, grid-forming, EMT	The project, and what happens next

SYNTHESIS

Three Things to Remember

1

Voltage is a system property, not a device

Devices, modes, taps and protection are designed together — or they fail together

2

Capability is not contribution

Verify what the fleet actually does when voltage moves — not the nameplate

3

Specify and prove the response

Define the service, size it, test it — and keep watching it

THE SEQUENCE

What to Do — and How Long It Takes

This month — free	Check control mode, protection settings, switching speed	A few reviews
This year — cheap	Automate switching; put margin on the screen; set the hierarchy	Months
This year — study	Rank weak buses; run Q–V; check strength; demand real models	Months
1–3 years	Reactors, MCR, SVC or STATCOM at the weak buses; monitoring	Assets
3–5 years	Condensers, series compensation, FACTS, reconductoring	Major assets

The top row costs nothing — and would have changed the outcome in Spain.

04 Closing poll

THIS ONE SHAPES THE STUDIES

RANK

Rank the following studies in the order that matters most for your system.

CHOOSE

What should a future webinar cover?

Thank you for your time and attention.

សូមអរគុណសម្រាប់ពេលវេលា និងការយកចិត្តទុកដាក់របស់អ្នក។

Ташаккур барои вақт ва диққати шумо.

E’tiboringiz va vaqtingiz uchun rahmat.

Спасибо за ваше время и внимание.

MRC TÜRKİYE

2026

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