재생에너지 확대 대비를 위한 인버터 기술 발전 현황 (Inverter Technology Development for Preparing the Expansion of DER

2022. 05. 17

한전 전력연구원 / 조종민
KEPCO Research Institute / Jongmin Jo

List

I. Status of Distributed Energy Resources

II. Increasing H.C for DER I – Voltage Management

III. Increasing H.C for DER II – Flexible Interconnection

IV. Grid Stability – Fault Ride Through

I Status of Distributed Energy Resources

Response of Climate Crisis

「2050 Carbon Net-Zero Emission」Global Agenda ➡ 138 Nations (2021.8)

SWEDEN	U.K	CANADA	FRANCE	NEWZEALAND	EU	CHINA	FINLAND	JAPAN	USA
Enactment	Enactment	Announce	Enactment	Enactment	LEDS	Announce	LEDS	Announce	President promise

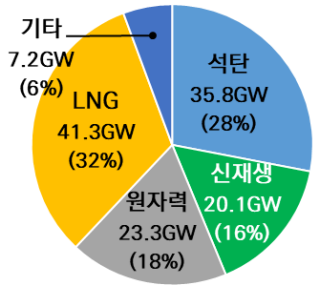
Step by step promotion of the government's '2050 Net-Zero Emission'

('21.6) 2050 Net-Zero Scenario* → ('21) Establishment of Key Policy → (~'23) National Plan Reflection

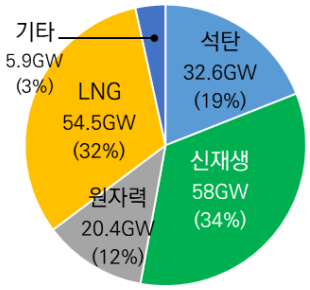
* Total 5 proposals (75% reduction in greenhouse gas compared to '17 , Gen. portions: Coal 4%/RE 60%) (출처 : 2050 Net-zero policy, '20.12)

Facility Capacity (제9차 전력수급기본계획 , '20.12)

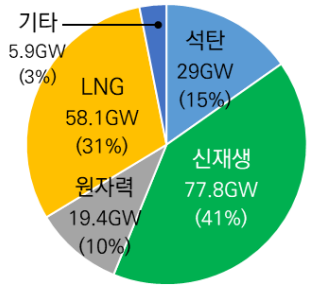
'20 RE 20.1GW



'30 RE 58GW



'34 RE 77.8GW



»

Offshore Wind

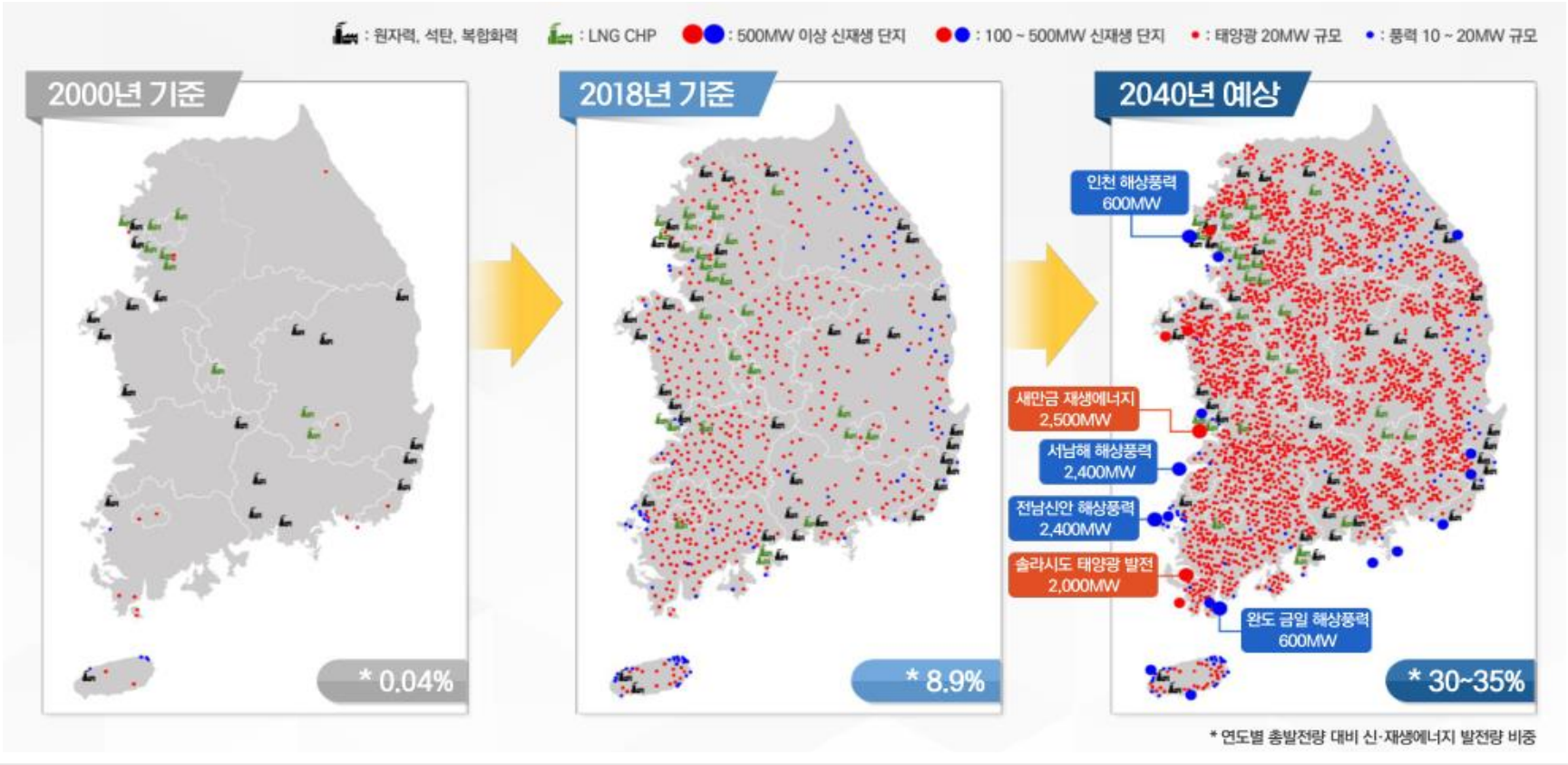
2030year
12GW

(Government's announcement, '20.7)

I Status of Distributed Energy Resources

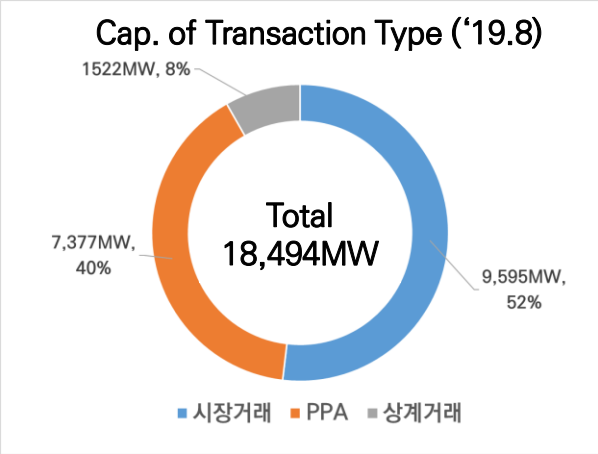
- Future's Energy System Prospects in Korea
  - Large-scale centralized long-distance ⇒ Small-scale production/consumption in the region

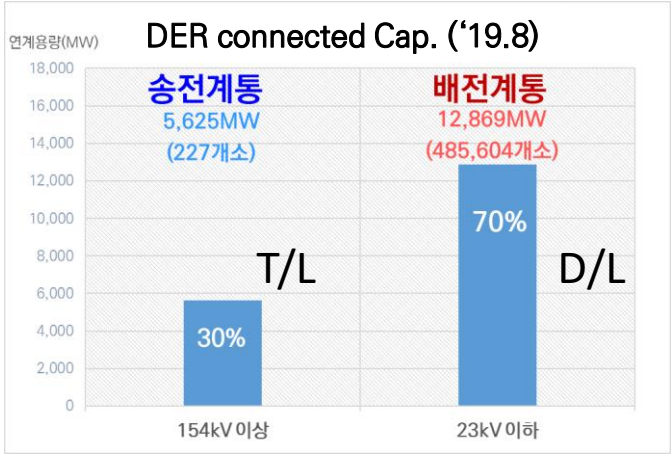
Transition to a Distributed Energy System (2040)

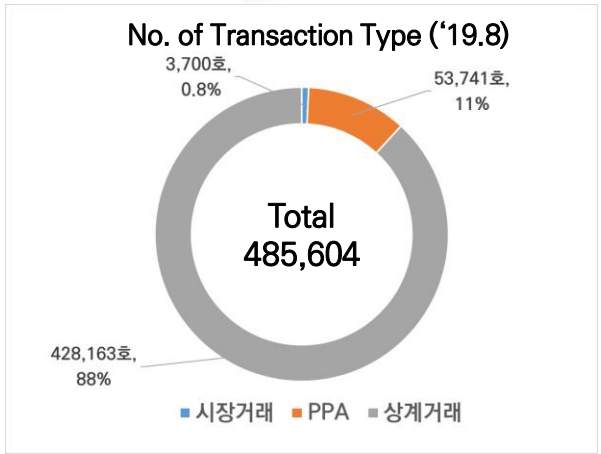


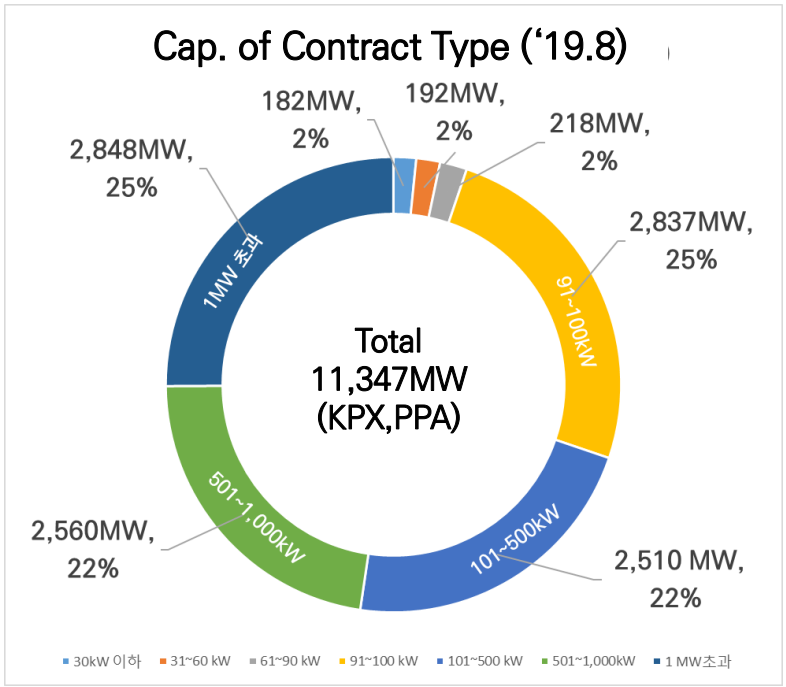
[Ref.] Measures to revitalize distributed energy led by regional initiatives (Ministry of Trade, Industry and Energy, '21.3)

I Status of Distributed Energy Resources









	Facility's Capacity					Total
	~ 90[kW]	90[kW] ~ 100[kW]	100[kW] ~ 500[kW]	500[kW] ~ 1[MW]	1[MW] ~	
No.	38,114	47,891	23,533	4,701	1,478	115,717
Cap. (MW)	1,202	4,712	5,255	4,111	3,248	18,528

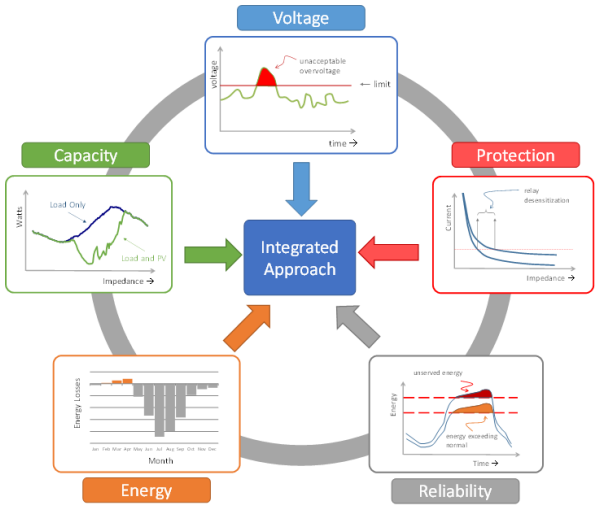
Status of DER with D/L (22.9[kV] or less) ('22.2)

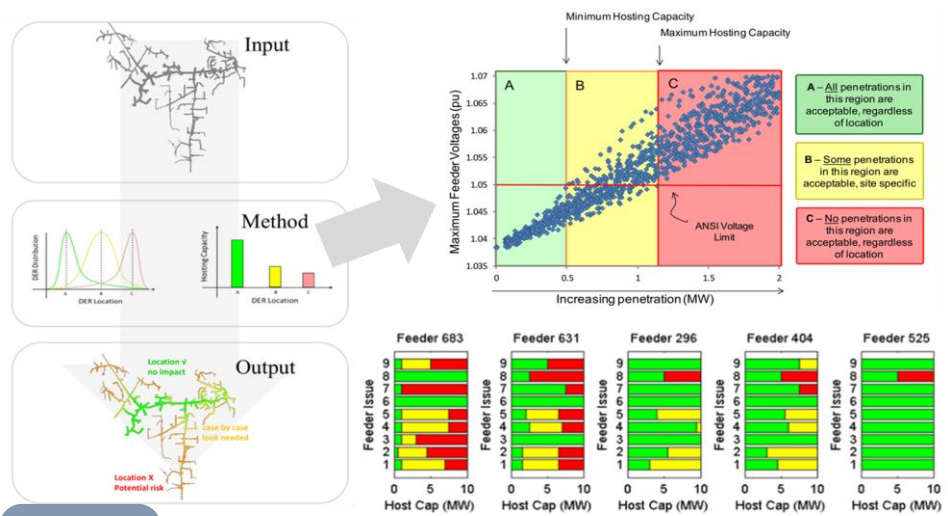
Ref. Hosting Capacity's Determining Factors

- Feeder hosting capacity for DER
  - Limiting hosting capacity : Over-voltage 75%, thermal overloading 25% (Xcel Energy)

Hosting Capacity's Determining Factors

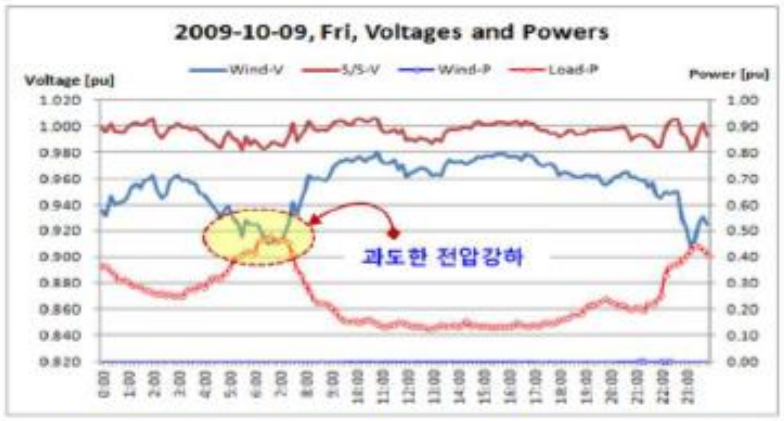
Thermal Limit	Voltage Quality	Protection Coordination	Reliability/Safety
Substation TR	Voltage Changes	Sympathetic operation	Power Islanding
Wired in MV grid	Permissible range	Under reach operation	Operational Flexibility
Pole TR	Voltage control scheme	Increase of fault current	Reconfiguration
Wired in LV grid	Tap control scheme	Reverse power flow	Resilience



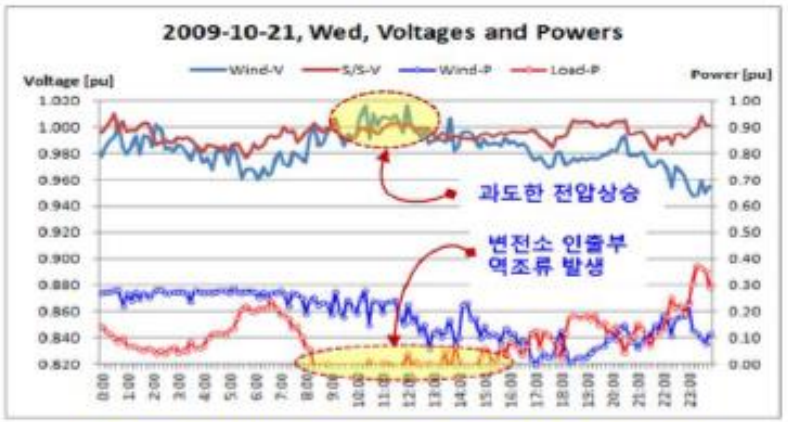


II Increasing H.C for DER I – Voltage Management

'D/L voltage must not deviate from the proper voltage due to DER connection'



[Without WT generation]



[With WT generation]

- ✓ (Method 1) New connected DER : Smart Inverter's grid support functions
- ✓ (Method 2) Legacy connected DER : Reactive Power Control of Monitor&Control Device
- ✓ (Method 3) Voltage managements cooperative control (OLTC + SVR + DER controls)

II Increasing H.C for DER I – Voltage Management

- (Method 1) New connected DER : Smart Inverter's grid support functions

→ Smart Grid Group Std. ('21.11), KEPCO grid code (T-'21.3, D-'21.12), KS standard ('22.9)

연번	기능	송전	배전
1	Volt-VAR	O	O
2	Q set point	O	O
3	Fixed Power Factor	O	O
4	Watt-Var	-	O
5	Volt-Watt	-	O
6	Frequency-Watt	O	O
7	P Limit	O	O
8	Normal-RAMP	O	O
9	Soft Start-RAMP	-	O
10	Low/High Voltage Ride-Through	O(Only LVRT)	O
11	Low/High Frequency Ride-Through	O	O
12	Power Stop	O	O
13	Disconnection and Reconnection	-	O
14	Anti-Islanding	-	O

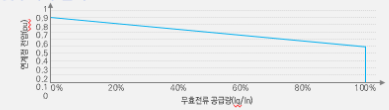
II Increasing H.C for DER I – Voltage Management

- KSGA-025-15-2 Functions of smart inverter for photovoltaic to support the power grid – Part2: Requirements and test methods for transmission system

전압 회복을 위한 무효전류 공급기준 및 유효전력 회복 기능

고장 중 무효전류 공급

풍력,태양광 및 연료전지발전기는 계통 전압 지원을 위해 고장 발생 후 3Cycle 이내에 아래그림을 만족하는 효전류공급능력을 갖추어야 한다.



고장 후 유효전력 회복

풍력,태양광 및 연료전지발전기는 고장제거 이후 연계점 전압이 연속운전 전압유지 범위로 복구된 후 5초 이내에 정상적인 전력공급을 할 수 있어야 함.

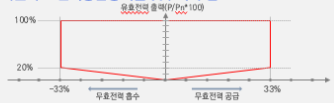
계통전압 불안정 현상 방지를 위해 신재생발전기 무효전력 공급기능

무효전력 공급능력

4) 무효전력 공급능력 성능유지

가) 풍력,태양광 및 연료전지발전기

① 운전전압 범위 내에서 아래와 같이 유효전력출력에 따른 무효전력공급능력을 갖추어야 함.



무효전력 제어능력

5) 무효전력 제어능력 성능유지

나) 풍력, 태양광 및 연료전지발전기는 다음 세 가지 무효전력 제어방식을 구비하여야 하며 계통운영자가 지시하는 기능을 수행할 수 있어야 함

① 일정 무효전력 출력제어 (Mvar 제어 모드)

② 일정 역률 제어 (PF 제어 모드)

③ 전압 조정을 위한 무효전력 제어(V-Q 제어 모드)

주파수 변동에 따른 유효전력 공급 및 제어기능

유효전력 제어능력 성능유지

6) 유효전력 제어능력 성능유지

가) 급 출력감소 조정 (연료전지 제외)

유효전력의 출력은 계통운영자의 지시 후 5초 이내에 정격 출력의 20%까지로 출력감소 할 수 있어야 함

나) 주파수 조정

풍력, 태양광 및 연료전지 발전기 인버터는 과·저 주파수 시 주파수 추종운전이 가능해야 하며, 주파수 변화에 따른 제어성능 구비필요

① 주파수 변화에 따른 속도조정률 : 3.0~5.0%

② 불감대 : 최대 0.06% 이내

주파수 특성

주파수 조정 및 유지범위는 58.5㎐ ~ 61.5㎐ 범위 내에서 연속 운전 가능

(계통주파수가 58.5㎐ ~ 57.5㎐ 범위에서 최소한 20초 이상 운전 가능)

신재생발전기 순간적 전압변동 및 고조파 발생 기준

전압변동

가) 전압변동

① 접속점에서 다음의 허용기준을 초과하지 않아야 함

전압변동률(%)	전압변동률 초과 빈도 제한
5	일일 4회 이하
3	한시간내 2회 이하
2.5	한시간내 2회 초과 10회 미만

고조파

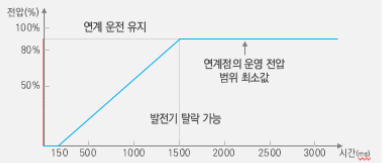
다) 신재생발전기는 계통에 연계시 접속점에서 다음 기준의 고조파를 초과하여 발생시켜서는 안 됨

송전계통	전압 종합 고조파 왜형률(%)
22.9 전용선로	5.0
70kV ~ 154kV	2.5
154kV 초과	1.5

저전압 라이드 스루(Ride-Through) 기능

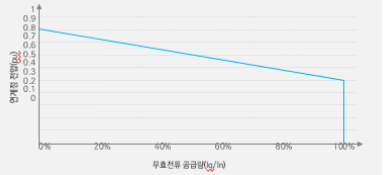
정상/비정상 전압상황에서 전력계통과의 연계 유지/분리 조건

저전압 계통연계 유지(LVRT)



구분	전압범위(%)	지속시간(초)
정상전압	90≤V≤110	연속운전
저전압 1단계	70≤V<90	1.2≤T<1.5
저전압 2단계	50≤V<70	0.9≤T<1.2
저전압 3단계	0≤V<50	0.15≤V<0.9

고장 중 무효전류 공급



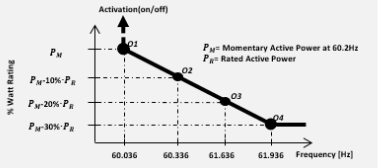
스마트 인버터는 계통전압 지원을 위해 고장발생 후 3 cycle 이내에 그림을 만족하는 무효전류 공급능력을 갖추어야 한다

스마트 인버터는 고장제거 이후 연계점 전압이 연속운전 전압유지 범위로 복구된 후 5초 이내에 고장 전 유효전력을 출력할 수 있어야 한다

주파수-유효전력 제어기능(Frequency/WATT)

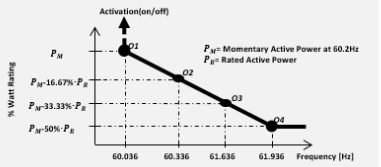
계통 주파수 변경시 스마트인버터 유효전력 출력제한 조건

주파수-유효전력 설정(속도조정률 5%)



운전점	주파수 목표점	주파수값(㎐)	유효전력 목표점	유효전력
O1	f1	60.036	P1	P_M
O2	f2	60.336	P2	P_M-10%·P_R
O3	f3	60.636	P3	P_M-20%·P_R
O4	f4	61.936	P4	P_M-30%·P_R

주파수-유효전력 설정(속도조정률 3%)



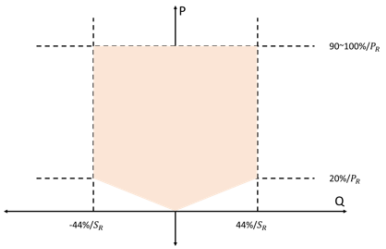
운전점	주파수 목표점	주파수값(㎐)	유효전력 목표점	유효전력
O1	f1	60.036	P1	P_M
O2	f2	60.336	P2	P_M-16.67%·P_R
O3	f3	60.636	P3	P_M-33.33%·P_R
O4	f4	61.936	P4	P_M-50%·P_R

II Increasing H.C for DER I – Voltage Management

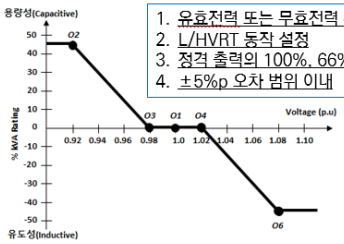
- KSGA-025-15-1 Functions of smart inverter for photovoltaic to support the power grid – Part1: Requirements and test methods for distribution system

Volt/Var(전압-무효전력 제어) 기능(5초 이내 응동)

- 정격 출력의(P_R) 20% 이상에서 정격 용량의(S_R) 최소 44%의 무효 전력을 공급/흡수



<무효전력 공급범위>



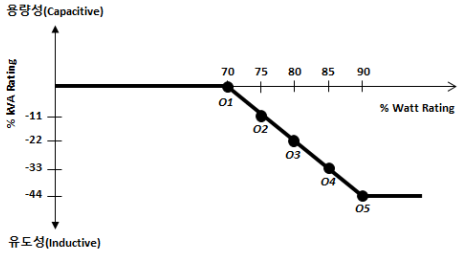
1. 유효전력 또는 무효전력 우선순위 설정
2. L/HVRT 동작 설정
3. 정격 출력의 100%, 66%, 20%에서 측정
4. ±5%p 오차 범위 이내

<Volt-Var 기본 곡선 예시>

운전점	전압 목표점	전압값(pu)	무효전력 목표점	무효전력(%)	동작
O1	Vref	1	Q1	0	단위 역률 (1.0 PF)
O2	V2	0.92	Q2	+44	무효전력 공급
O3	V3	0.98	Q3	0	단위 역률 (1.0 PF)
O4	V4	1.02	Q4	0	단위 역률 (1.0 PF)
O5	V5	1.08	Q5	-44	무효전력 흡수

<Volt-Var 기본 설정값 예시>

Watt/Var(유효전력-무효전력 제어) 기능(5초 이내 응동)



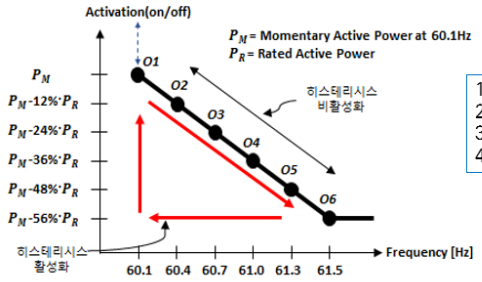
1. 정격 출력에서 동작
2. ±5%p 오차 범위 이내

운전점	유효전력(%)	무효전력(%)	동작
O1	70	0	단위 역률 (1.0 PF)
O2	75	-11.0	무효전력 흡수
O3	80	-22.0	무효전력 흡수
O4	85	-33.0	무효전력 흡수
O5	90	-44.0	무효전력 흡수

<Watt-Var 기본 곡선 및 설정값 예시>

Frequency-Watt(주파수-유효전력 제어) 기능(1초 이내 응동)

- 히스테리시스 활성화/비활성화 설정(기본 설정값은 비활성화)



1. 정격 출력으로 운전
2. L/HFRT 동작 설정
3. 히스테리시스 기능 지원 시 동작 확인
4. ±2.5%p 오차 범위 이내

운전점	주파수 목표점	주파수값(Hz)	유효전력 목표점	유효전력	동작설정
O1	f1	60.1	P1	P_M	기능 활성화 주파수 60.1Hz(배전)
O2	f2	60.4	P2	P_M-12%·P_R	
O3	f3	60.7	P3	P_M-24%·P_R	
O4	f4	61.0	P4	P_M-36%·P_R	
O5	f5	61.3	P5	P_M-48%·P_R	
O6	f6	61.5	P6	P_M-56%·P_R	

<Frequency-Watt 기본 곡선 및 설정값 예시>

Normal Ramp Rate(출력 램프율) 기능

- 정상 운전 상황에서 출력의 변화율 제한(제어 대상은 Watt, VAR, PF)

구분	단위	기본값	설정 범위
출력 램프율 활성/비활성화	활성/비활성	활성	활성/비활성
출력 램프율	%Irated/s	100	1~200

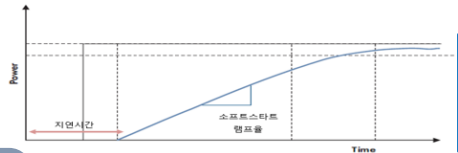
<출력 램프율 설정 값>

1. 정격 및 최소 출력으로 운전
2. 최소/평균/최대 출력 램프율에서 결과 측정
3. ±2.5%p 오차 범위 이내 (유효전력 목표값이 5% 이상의 경우에서)

Soft Start Ramp Rate(소프트 스타트 램프율) 기능

- 계통과 전기적 분리 및 재연계 시 출력의 변화율 제한(제어 대상은 Watt, Var, PF)

구분	단위	기본값	설정 범위
소프트 스타트 램프율 활성/비활성화	활성/비활성	활성	활성/비활성
소프트 스타트 지연시간	초	300	0~600
소프트 스타트 램프율	%Irated/s	2	1~200

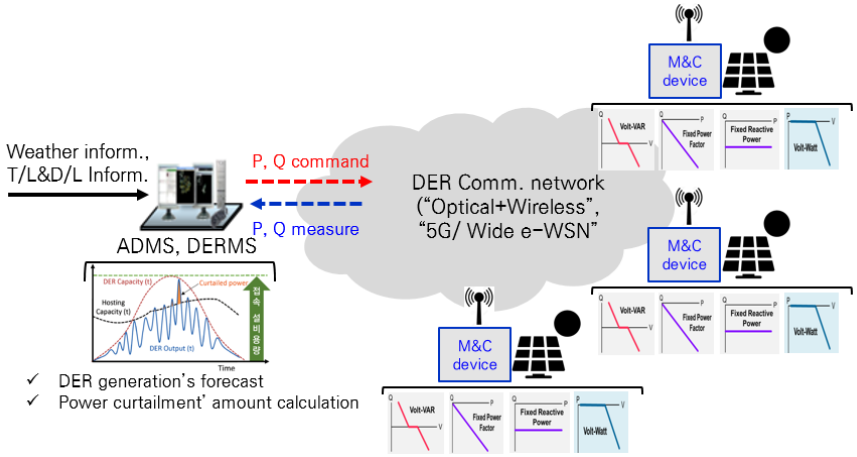


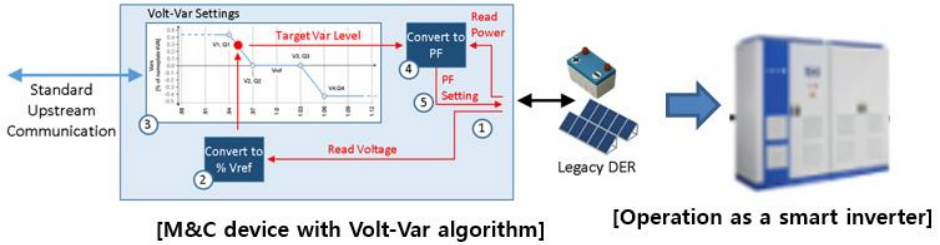
<소프트 스타트 출력 램프율 설정 값 및 곡선>

1. 정격출력으로 운전
2. 계통과 분리, 재연계 수행 시 SS-RAMP 동작 확인
3. 지연시간 및 램프율 변경
4. ±2.5%p 오차 범위 이내 (유효전력 목표값이 5% 이상의 경우에서)

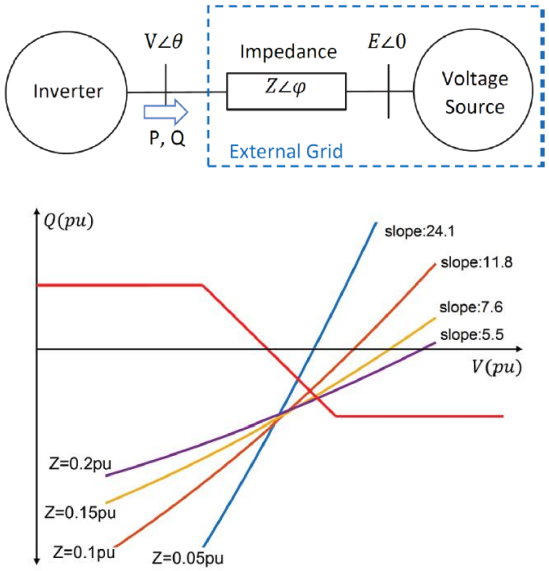
II Increasing H.C for DER I – Voltage Management

- (Method 2) Legacy connected DER : Reactive Power Control of Monitor&Control Device

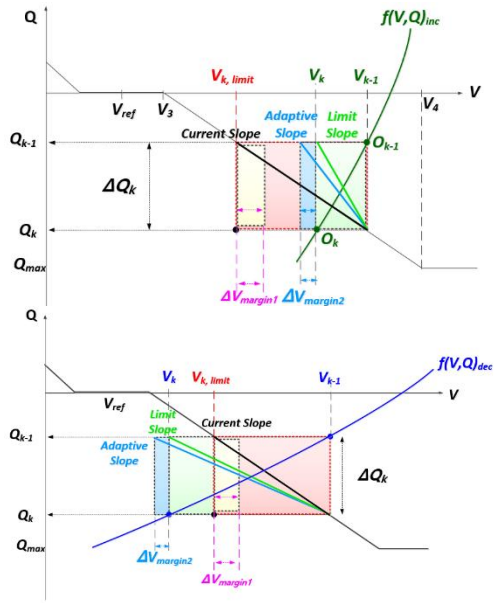




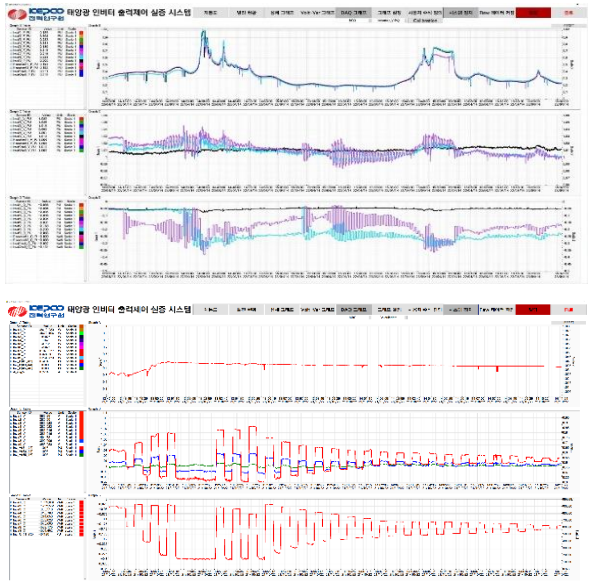
Mechanism/Stability Analysis



Development of Control Algorithm



On-site Verification



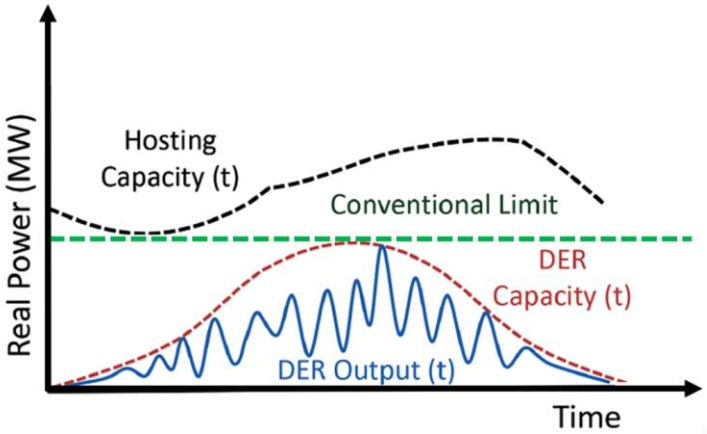
III Increasing H.C for DER II – Flexible Interconnection

As-Is

DER Fixed Interconnection

DER Hosting Cap. = DER Installed Cap.

- Suitable for low connected DER
  - Priority for grid stability
- Requirement of reinforcement facilities when DER connection increases
  - Increased investment cost

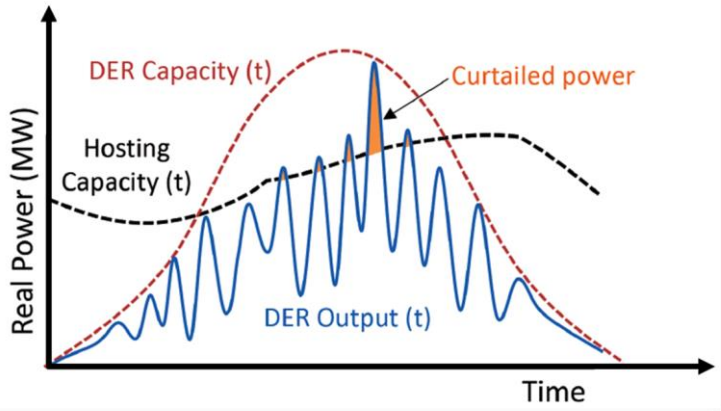


To-Be

DER Flexible Interconnection

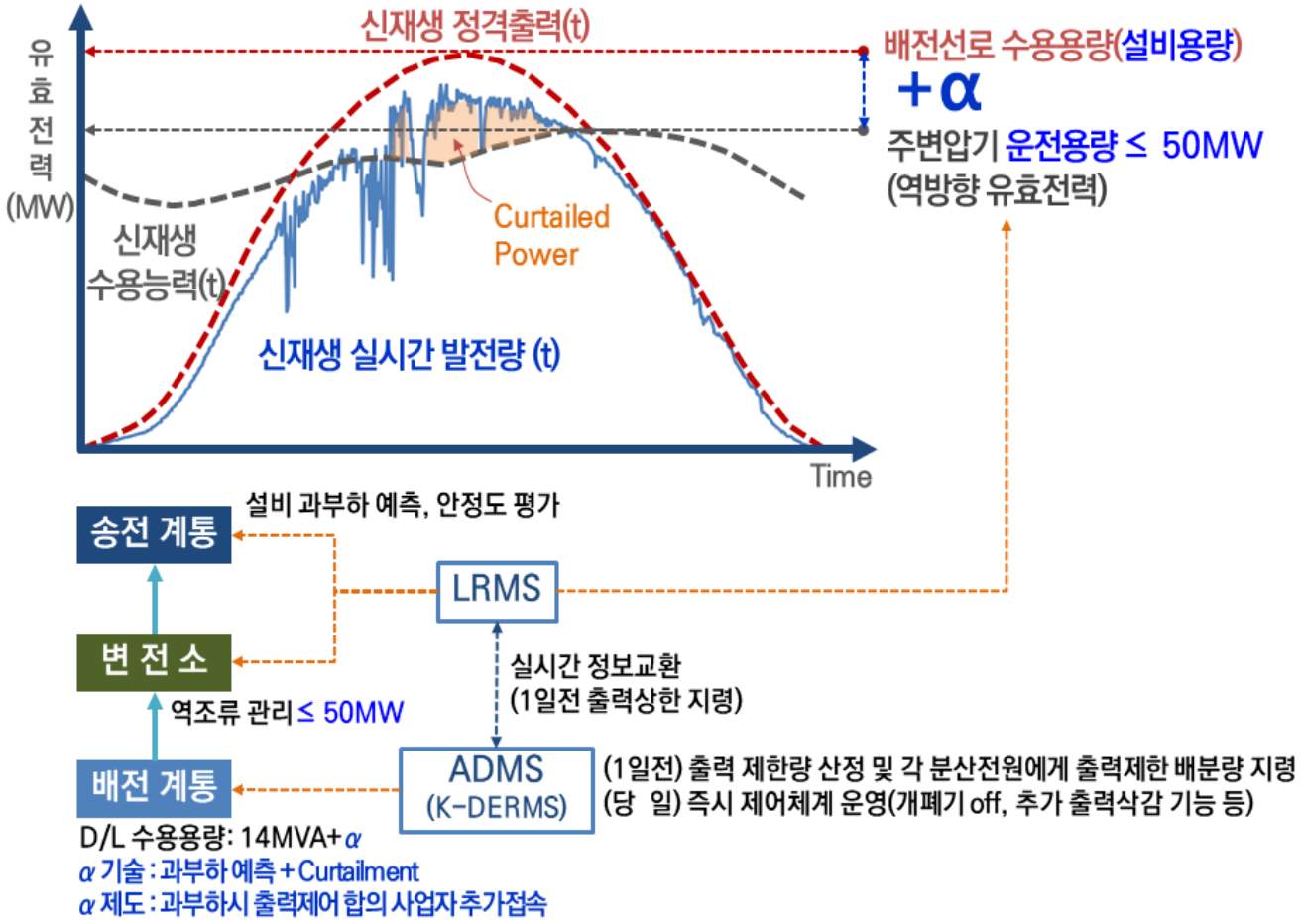
DER Hosting Cap. = DER Operating Cap.

- Needs to be applied when the DER connection increases
  - Minimize investment cost
- Control method after pre-connection
  - Monitoring and control tech.



※ 그림 출처 : EPRI, "PRINCIPLES OF ACCESS FOR FLEXIBLE INTERCONNECTION : COST ALLOCATION MECHANISMS AND FINANCIAL RISK MANAGEMENT", 2020

III Increasing H.C for DER II – Flexible Interconnection



- M.TR in substation hosting capacity standard ：Installed Cap. 50[MW] → Operating Cap. 50[MW]
- Distributed Line hosting capacity : Installed Cap. 12[MW] → Installed Cap. 14[MW] + α

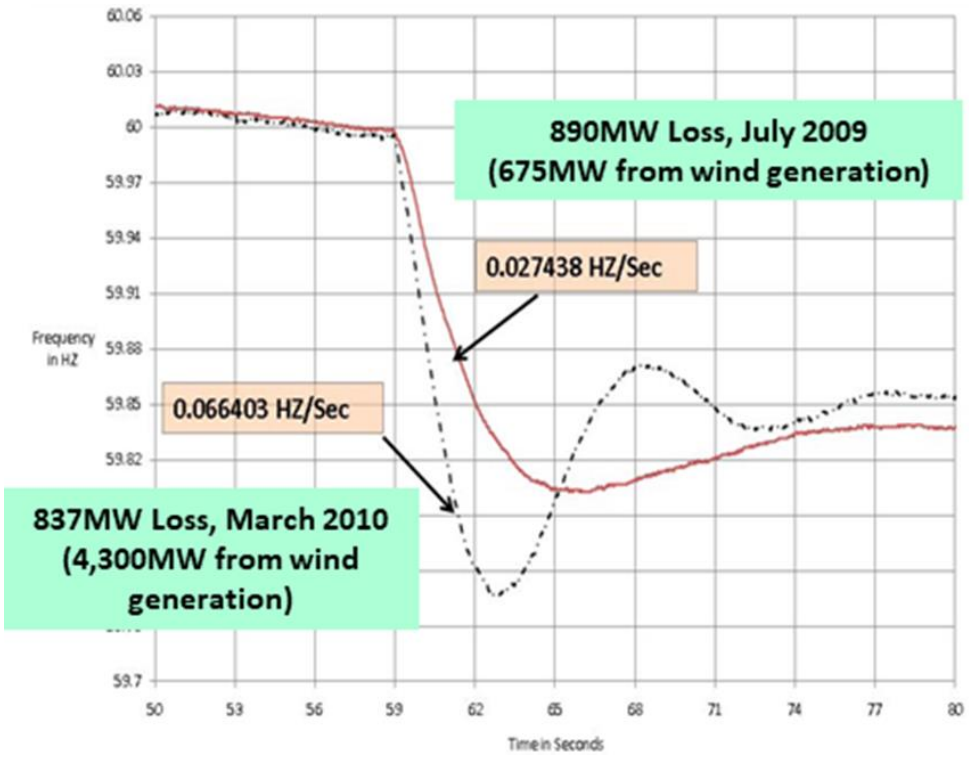
  → DER with accumulated Cap. exceeding 12[MW] are conditionally connected (P curtailment)

IV Grid Stability – Fault Ride Through

- Increase in DER based on PCS(Inverter) : Reduction of grid inertia

  Grid code: 'Frequency Ride-Through' requirement → maintains P gen. even when Freq. drops

Reduction of inertial energy due to DER increase → Rate of change of frequency



- Grid fault example in Texas
  - Similarities : Loss of same-scale power generation

    890MW('09) → 837MW('10)
  - Difference : Increase WT gen.

    675MW('09) → 4,300MW('10)
  - Inertia decrease due to the DER increase of DER
  - Increase in frequency drop
  - Possibility of dropping out of additional DER

IV Grid Stability – Fault Ride Through

- Freq. drop due to grid fault ⇒ Thermal-electric & RE plant loss ⇒ Large-scale blackout
  - 400kV T/L ground fault (Lightning strike) ⇒ Instantaneous (80ms) voltage drop ⇒ Plant shutdown ⇒ Freq. drop

Large-scale blackout in UK: 2019. 8. 9. 16:52

The Guardian

National Grid blames lightning strike for blackout

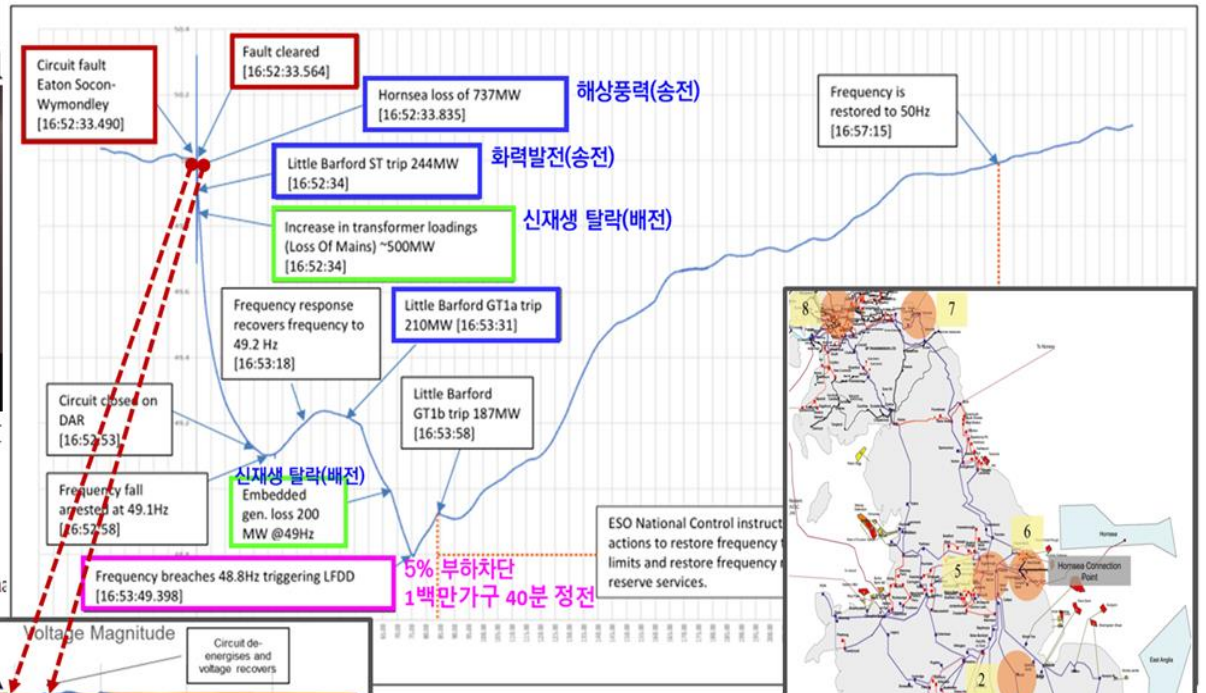
Ofgem to launch investigation after two power generators tripped offline

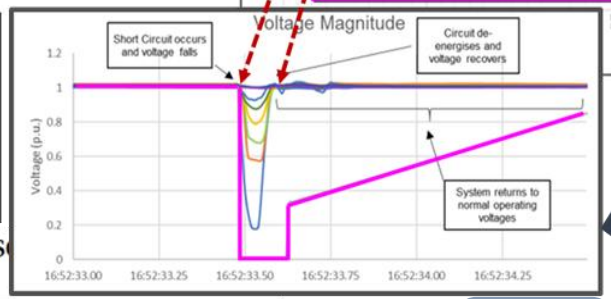
Jillian Ambrose, *energy correspondent, and* **Gwyn Topham**

Tue 20 Aug 2019 07.41 BST

National Grid has blamed a lightning strike for Britain's biggest blackout in more tha
after it caused two power generators to go offline.

What are the questions rais
blackout?





송전선로 낙뢰고장, 전압강하

IV Grid Stability – Fault Ride Through

Correlation between inverter-based DER Increase and grid stability

RE Increase
Asynchronous RE (PV, WT) Connection Increase

Variability Increase
Weather dependence, Diff. in supply manage

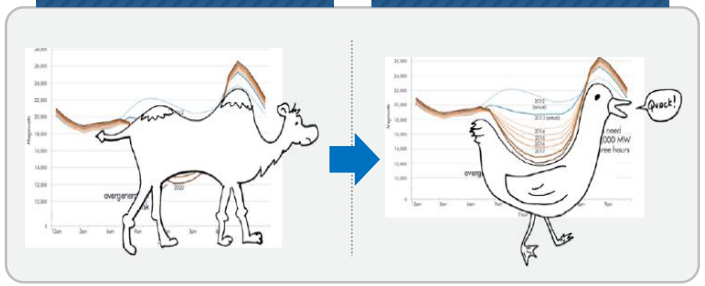
Diff.(Supply/demand)
Demand variability + Supply variability

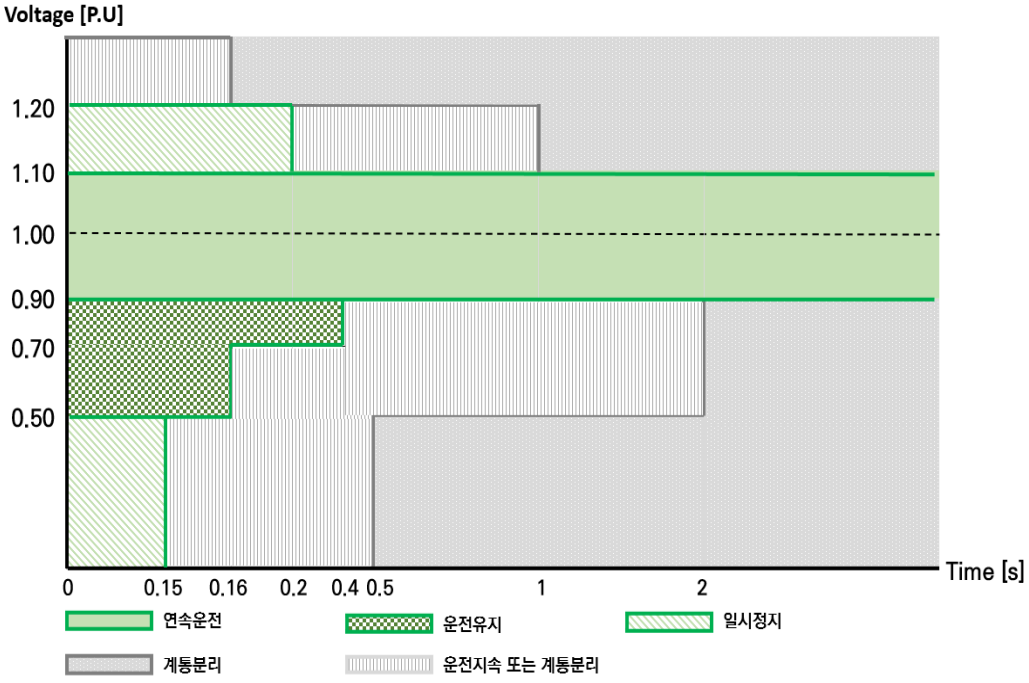
Replace Existing Gen.
RE capacity ↑ Synchronous gen. ↓

Weak System
Inertia, Short-circuit Cap. ↓

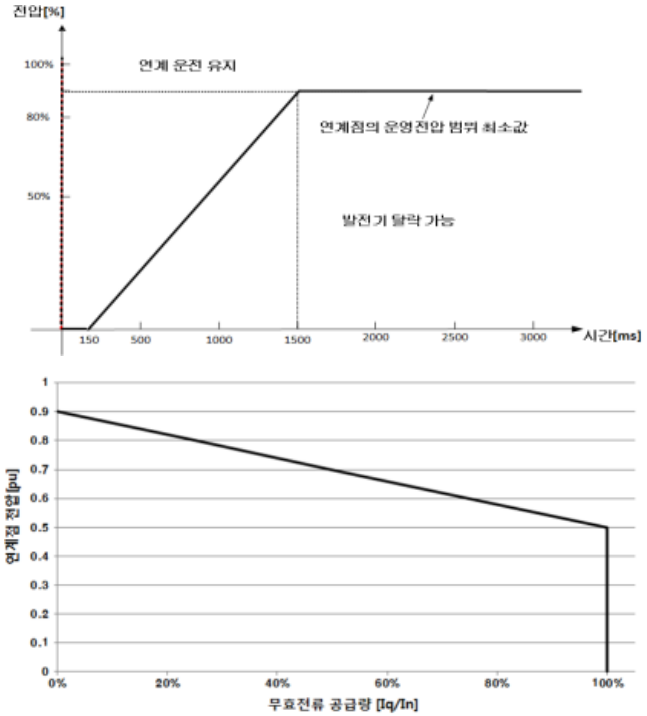
Reduced Stability
- Freq. stability
- Angle stability
- Voltage stability

Carmel Curve / **Duck Curve**





[L/HVRT curve of Distribution System]

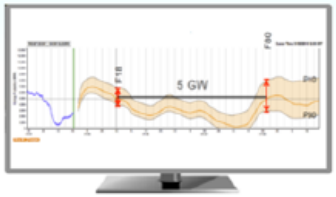


[LVRT curve of Transmission System]

In the Future..

National-wide Renewables Management System (Plan)

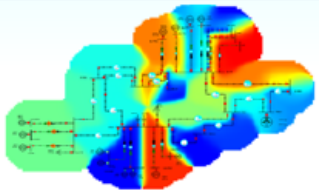
Stochastic forecasting for renewable output



Estimating over-generation

RMS(monitor & control)

Online stability analysis

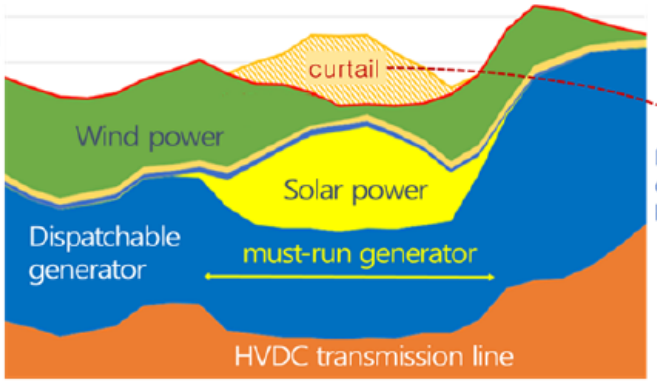


Grid over-loading analysis

Curtailment & dispatch (Remote control)

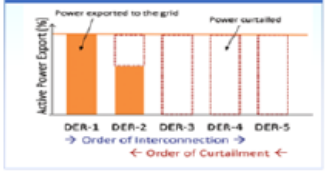
Balancing Supply & Demand

Grid stability



Priority dispatch by rule

Last-in-first-out

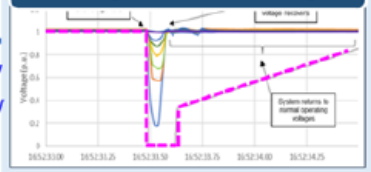


Equally limiting output

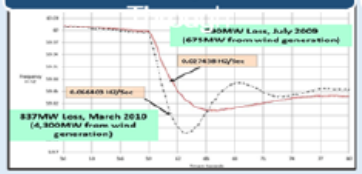
Setting value (Autonomous control)

Fault stability
Power quality

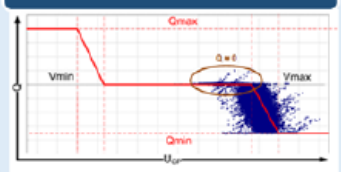
Voltage Ride-Through



Frequency Ride-



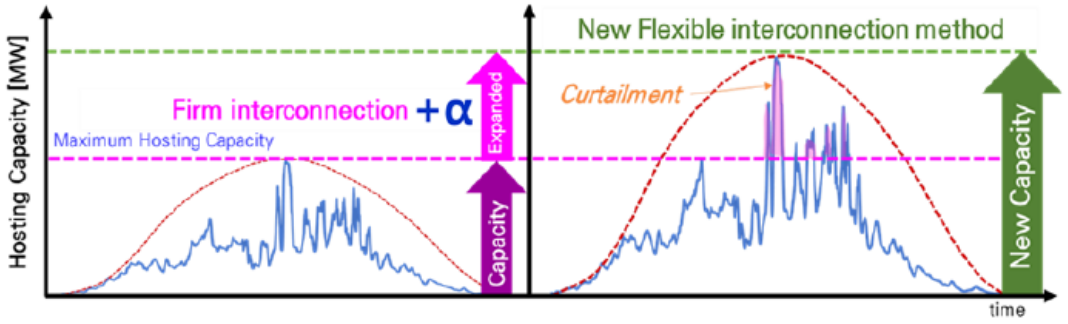
Volt-Var Function



Protecting from over-loading

Increasing hosting capacity

Curtailment of peak (Remote control)



- (Real-time) Establishment and Linkage of integrated control system : RMS ↔ LRMS ↔ ADMS

THANK YOU

KEPCO