NOVA

Power / Energy Track

Optical Power Flow in Microgrids With Energy Storage

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01 Introduction

전력계통 : 공식을 배우며 그 공식의 원천을 공부하는 분야

전력계통 : 전력을 생산 및 송배전을 얼마나 효율적이게 다루는가

- 논문 분석 및 강의를 들으면서 초기 전력계통의 정의에 오류가 발생

01 Introduction

Abstract—Energy storage may improve power management in microgrids that include renewable energy sources. The storage devices match energy generation to consumption, facilitating a smooth and robust energy balance within the microgrid. This paper addresses the optimal control of the microgrid's energy storage devices. Stored energy is controlled to balance power generation of renewable sources to optimize overall power consumption at the microgrid point of common coupling. Recent works emphasize constraints imposed by the storage device itself, such as limited capacity and internal losses. However, these works assume flat, highly simplified network models, which overlook the physical connectivity. This work proposes an optimal power flow solution that considers the entire system: the storage device limits, voltages limits, currents limits, and power limits. The power network may be arbitrarily complex, and the proposed solver obtains a globally optimal solution.

Index Terms—Distributed generation (DG), energy storage, microgrid, optimal power flow (OPF), smart grid.

논문이 말하고자 하는 것

에너지 저장 장치를 포함한 마이크로그리드

실제 계통 제약(조건)까지 고려한 최적 전력조류

에너지 저장장치 최적 제어 방법

기존 시스템 비판 – 개선을 한 점

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마이크로그리드 : 부하, 저장 장치, 소형 발전기들의 모임 (네트워크)

연결 방식 : 공통 접속을 통한 공용 전력망에 연결

기술 : 신재생 에너지(태양, 풍력 등) 및 동기 발전기, 배터리, 연료 전지 등

특징 : 부하 근처에서 전력을 생산

-전력망 신뢰성 향상

-장거리 송전 선로에서 전력 손실 감소

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마이크로그리드 : 부하, 저장 장치, 소형 발전기들의 모임 (네트워크)

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3차 제어(Tertiary) : 능동 및 무효 전력의 흐름을 최적화하고 효율적으로 배분하는 단계

01 Introduction

마이크로그리드의 분류 : 연결 상태

독립형 : 시스템의 주파수, 전압 안정화 목표

계통 연계형 : PCC에서의 에너지 수입 비용 최소화, 역률 개선, 전압 최적화

PCC : 공통 접속점, 공용 전력망에 연결되는 지점

02 Background – 네트워크 토폴로지 및 (Bus) 신호

전력망 분석을 위한 접속점(Bus)의 독립적인 신호 4가지

- $P_i(t)$—the active power, injected from the bus into the grid (positive for generators, negative for loads);
- $Q_i(t)$—the reactive power, injected into the grid;
- $V_i(t)$—the voltage magnitude of the bus;
- $\delta_i(t)$—the phase angle of the voltage V_i.

능동 전력 : 접속점에서 그리드로 주입되는 전력

무효 전력 : 그리드로 주입되는 무효 전력

전압 크기 : 접속점(버스)의 진폭

위상각 : Vi 전압의 위상

02 Background – 전력 조류 방정식

평형 3상 시스템

$$P_i = V_i \cdot \sum_{j=1}^{N} Y_{ij} \cdot V_j \cdot \cos(\delta_i - \delta_j - \theta_{ij})$$

$$Q_i = V_i \cdot \sum_{j=1}^{N} Y_{ij} \cdot V_j \cdot \sin(\delta_i - \delta_j - \theta_{ij})$$

$$I_{ij} = \left| V_i \cdot e^{i\delta_i} - V_j \cdot e^{i\delta_j} \right| .$$

이때 i, j는 x, y가 아닌 버스(bus, 모선) ex Via = i번 버스의 a상 전압

02 Background – 전력 조류 방정식

불평형 3상 시스템

$$P_{i,x} = V_{i,x} \cdot \sum_{j=1}^{N} Y_{ij,x} \cdot V_{j,x} \cdot \cos(\delta_{i,x} - \delta_{j,x} - \theta_{ij,x})$$

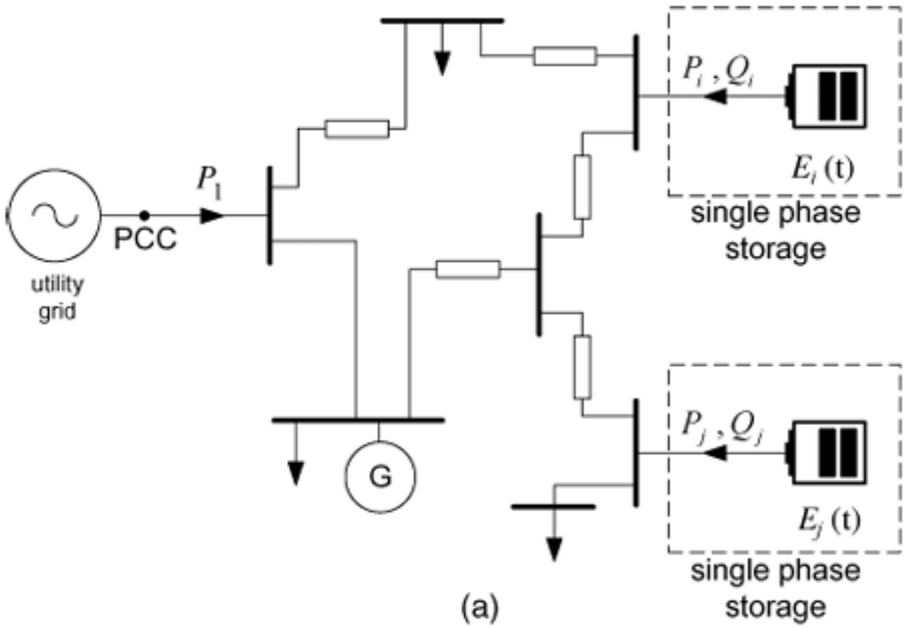
$$Q_{i,x} = V_{i,x} \cdot \sum_{j=1}^{N} Y_{ij,x} \cdot V_{j,x} \cdot \sin(\delta_{i,x} - \delta_{j,x} - \theta_{ij,x})$$

$$I_{ij,x} = \left| V_{i,x} \cdot e^{i\delta_{i,x}} - V_{j,x} \cdot e^{i\delta_{j,x}} \right|$$

이때 x는 불평형 시스템을 의미하기 위함 – 개별 기호

02 Background – 전류 조류 방정식

PCC(슬렉 버스)



1번 버스로서 시스템의 전력 수급 균형을 맞추는 기준점

02 Background – 에너지 저장 장치(ESS)

상태 변수(E) : 저장되는 에너지 이때 다른것은 시간에 따라 변한다.

상태 방정식 : 에너지가 시간에 따라 어떠하게 변화되는가 – 3상 저장도 있음

$$\frac{d}{dt}E_i = f_i(P_i, E_i).$$

$$\frac{d}{dt}E_i = f_i(P_{i,A}, P_{i,B}, P_{i,C}, E_i)$$

02 Background – 목적 함수

현재 이 논문에서 말하는 시스템의 최적화 모델을 수학적으로 정의

C(t) : 가격 신호 시간에 따라 변화하는 에너지 단가를 고려함

$$\int_0^T P_1(t) \cdot C(t)dt \to \min$$

$$\int_0^T (P_A(t) - P_B(t))^2 + (P_B(t) - P_C(t))^2 \, dt \to \min .$$

03 Related Work

기존 연구 분류

1. 분산 발전기 배치 및 공유
2. 경제적 수익 극대화
3. 에너지 저장 장치(ESS)의 최적 배분

03 Related Work

기존 연구 분류

1. 분[illegible]기 배치 및 공유
2. 경제적 수익 극대화
3. 에너지 저장 장치(ESS)의 최적 배분

한계 : 네트워크 모델을 무시한 단순화 모델

복잡한 전력망 구조에 저장 장치가 통합된 경우 없음

수치적 복잡성

경사 기반 문제의 한계

04 Dynamic Programming

does not resemble the global one and have no desired properties. This local solution is unsuitable and cannot be used in a real power system.

IV. Dynamic Programming Approach

Unlike gradient-based methods, dynamic programming algorithms (see [18]) scan all feasible solutions to locate the global optimum. A direct scan of the entire solution space is numerically impossible, so the optimal solution is designed recursively, combining dynamic allocation in the time domain, with a traditional power flow solver on the network domain.

A. Single Storage Device—One-Dimensional Solution

With a single one-phase storage device, the stored energy function $E_i(t)$ governs the power flow of the network. For a given energy function, the power output of the storage device $P_i(t)$ may be computed using the storage state (3). Assuming that the voltage magnitude of the device is specified, $V_i(t) = V_{S,i}$, the device may be replaced by an auxiliary P–V unit, with known power and voltage values. Recall that loads and renewable generators are specified, so given the storage power output, power flow over the entire network may be computed. This is easily achieved using standard power flow algorithms, such as Gauss–Seidel, or Newton–Raphson. The problem is therefore one-dimensional, with a single controllable state variable $E_i(t)$.

The challenge is to determine the energy function $E_i(t) = E(t)$ that minimize the objective equation (5) and comply with all constraints listed in Table I. To this end, a value function $V(\cdot)$ is defined as

$$V(t,E) = \int_t^T P_1(\tau)\cdot C(\tau)\cdot d\tau \quad (8)$$

with an initial condition $E(t) = E$

The objective equation (5) is equivalent to minimizing $V(0,0)$, that is, to minimize overall cost over the entire period, starting with an empty storage $E = 0$. Calculations are numeric, over a discrete grid. dt marks the time step, and dE marks the energy step. The optimal solution is computed recursively by the Bellman equation

$$V(t,E) = \min_{E(t+dt)} \{\Delta V(E, E(t+dt)) + V(t+dt, E(t+dt))\} \quad (9)$$

The value function $V(t,E)$ is numerically computed by backward recursion. The process starts at the final time $t = T$, where the value function is known: $V(T,E) = 0$. Applying (9), the value function may be computed at $T - dt$, revealing $V(T-dt, E)$ over all the energy values. The process continues until reaching $t = 0$. A backward recursion step is shown at Fig. 4(a).

The differential cost ΔV is defined for every two arbitrary points $\{t, E(t)\}$ and $\{t+dt, E(t+dt)\}$. It represents the cost of transition between the two points. ΔV is computed in the following steps.

Step 1) The first derivative of energy is evaluated by

$$\frac{d}{dt}E \approx \frac{E(t+dt) - E(t)}{dt}. \quad (10)$$

Step 2) Power output of the storage device, $P_i(t)$, is evaluated. The storage state (3) is solved using known values of $E(t)$ and its first derivative $E(t)$, revealing $P_i(t)$.

Step 3) The storage device is replaced with an auxiliary P–V source, with $P = P_i(t)$, $V = V_{S,i}$. A network power flow analysis is computed using Gauss–Seidel, Newton–Raphson, or any other method.

Step 4) If the power flow solution complies with all network constraints, the differential ΔV is assigned a value according to the power at the PCC, $P_1(t)$. Otherwise, it is assigned a value of infinity

$$\Delta V = \left\{\begin{array}{ll} P_1(t)\cdot C(t)\cdot dt, & \text{in constraints} \\ \infty, & \text{otherwise} \end{array}\right\}. \quad (11)$$

Having computed $V(t,E)$ over all times and energies, the optimal energy $E^*(t)$ may be evaluated. This is done by a forward recursion process. Known values of $V(t,E)$ are substituted in the Bellman equation to recover the optimal solution

$$E^*(t) = \arg\min_{E(t)} \{\Delta V(E^*(t-dt), E(t)) + V(t, E(t))\} \quad (12)$$

Energy at t and $E^*(t)$ is calculated in relation to a previous energy value $E^*(t-dt)$. The computation process starts at $t = 0$, in which optimal energy is known and equals the starting condition, usually $E^*(0) = 0$. Optimal energy at the next time step $E^{ast}(dt)$ is evaluated by (12). The process continues until the entire optimal energy path has been discovered, up to the final time $t = T$. Knowing the optimal energy path, all powers, voltages, and phase angles may be computed directly.

B. Multiple Storage Devices

Each storage device adds a dimension to the solution space. Thus, a network with two storage devices is a two-dimensional (2-D) problem, with two free variables: $E_i(t)$ and $E_j(t)$. Power flow is now governed by two energy functions instead of one. A 2-D computation is shown in Fig. 4(b).

Multidimensional solutions are essentially equivalent to single dimension solutions. The major difference is that the value function, $V(\cdot)$ is now multidimensional. Consider, as an example, a one-phase network with two storage devices. The value function is now defined as follows:

$$V(t, E_i, E_j) = \int_t^T P_1(\tau)\cdot C(\tau)\cdot d\tau \quad (13)$$

initial condition

$$E_i(t) = E_i,\ E_j(t) = E_j.$$

It is a function of both $E_i(t)$ and $E_j(t)$. The Bellman equation now involves minimization over both energy variables

$$V(t, E_i, E_j) = \min_{\substack{E_i(t+dt),\\ E_j(t+dt)}} \{\Delta V(E_i, E_i(t+dt), E_j, E_j(t+dt)) + V(t+dt, E_i(t+dt), E_j(t+dt))\} \quad (14)$$

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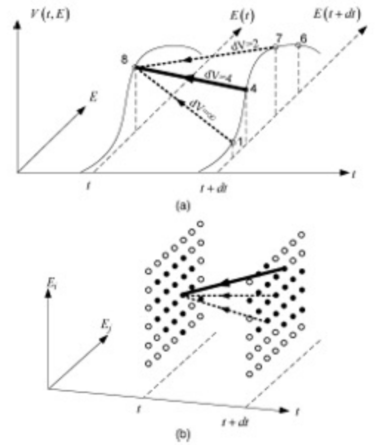

Fig. 4. Backward recursion process, using the Bellman equation. The value function at each point equals the minimum over all differential paths from t to $t + dt$. Possible paths appear as dashed lines, and the optimal path is marked bold. (a) Single storage device, with one state variable $E(t)$. (b) Multidimensional—two storage devices with two variables—$E_i(t)$, $E_j(t)$. White dots mark the numerical grid. Black dots mark feasible solutions.

The differential cost ΔV is computed for 2-D points $\{t, E_i(t), E_j(t)\}$ and $\{t+dt, E_i(t+dt), E_j(t+dt)\}$ [see Fig. 4(b)]. The computation involves evaluation of two derivatives as

$$\frac{d}{dt}E_i \approx \frac{E_i(t+dt) - E_i(t)}{dt}$$
$$\frac{d}{dt}E_j \approx \frac{E_j(t+dt) - E_j(t)}{dt}. \quad (15)$$

These are employed for computing the output power of both storage devices. Using this data, the network power flow is evaluated normally, at each time point, using Gauss–Seidel, or Newton–Raphson. The differential ΔV is assigned a value according to the power at the PCC or assigned a value of infinity in case the solution is infeasible.

Three phase storage devices may be 1-D or 3-D. A balanced three-phase device, with equal powers $P_{i,A} = P_{i,B} = P_{i,C}$, is 1-D. The stored energy $E(t)$ determines the three phase powers, in accordance with the storage state equation (4). Knowing the storage output powers, a three-phase power flow analysis is computed at each time point. If phase powers are each individually controlled, using a dedicated power converter, than the problem is 3-D. The free variables may be $P_{i,A}(t), P_{i,B}(t), P_{i,C}(t)$.

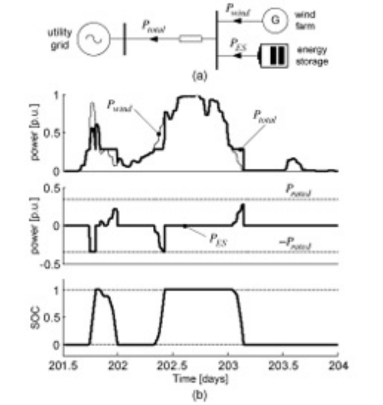

Fig. 5. Power system of Brekken *et al.* [16]. (a) Wind farm and storage. (b) Optimal solution. Top: wind power and total power. Middle: storage power. Bottom: battery SOC.

V. Microgrid Case Study I

To demonstrate the proposed method, we examine a power system proposed by Brekken *et al.* [16]. The system [Fig. 5(a)] includes a wind farm (renewable source), coupled with a battery energy storage. During high winds, energy is stored in the battery. Stored energy is released when wind is low, smoothing total power injected to the grid.

The following description is duplicated from [16]: wind power is represented by P_{wind}, storage power is P_{ES}, and total power is P_{total}. The battery is modeled by its power capacity P_{rated}, the storage capacity J_{rated}, and the battery State of Charge (SOC), in the range 0,..,1. This represents energy in this problem. The storage state equations are

$$\frac{d}{dt}\mathrm{SOC} = -\frac{\eta\cdot P_{ES}}{J_{rated}}$$
$$\eta = \left\{\begin{array}{ll} \eta_{out}, & P_{ES} > 0 \\ \eta_{in}, & P_{ES} < 0 \end{array}\right\}$$
$$-P_{rated} \le P_{ES} \le P_{rated}$$
$$0 \le \mathrm{SOC} \le 1. \quad (16)$$

The parameters are chosen as follows: $P_{rated} = 0.34$, $J_{rated} = 0.4$, $\eta_{in} = 0.85$, and $\eta_{out} = 1.15$. Wind power P_{wind} is sampled from [16].

The proposed dynamic programming analysis is applied to this system, optimizing the utilization of storage. A price signal is unavailable, so a minimal price objective cannot be evaluated. Instead, we chose to optimize the power output of the system by minimizing losses over the mutual power line. Assuming a

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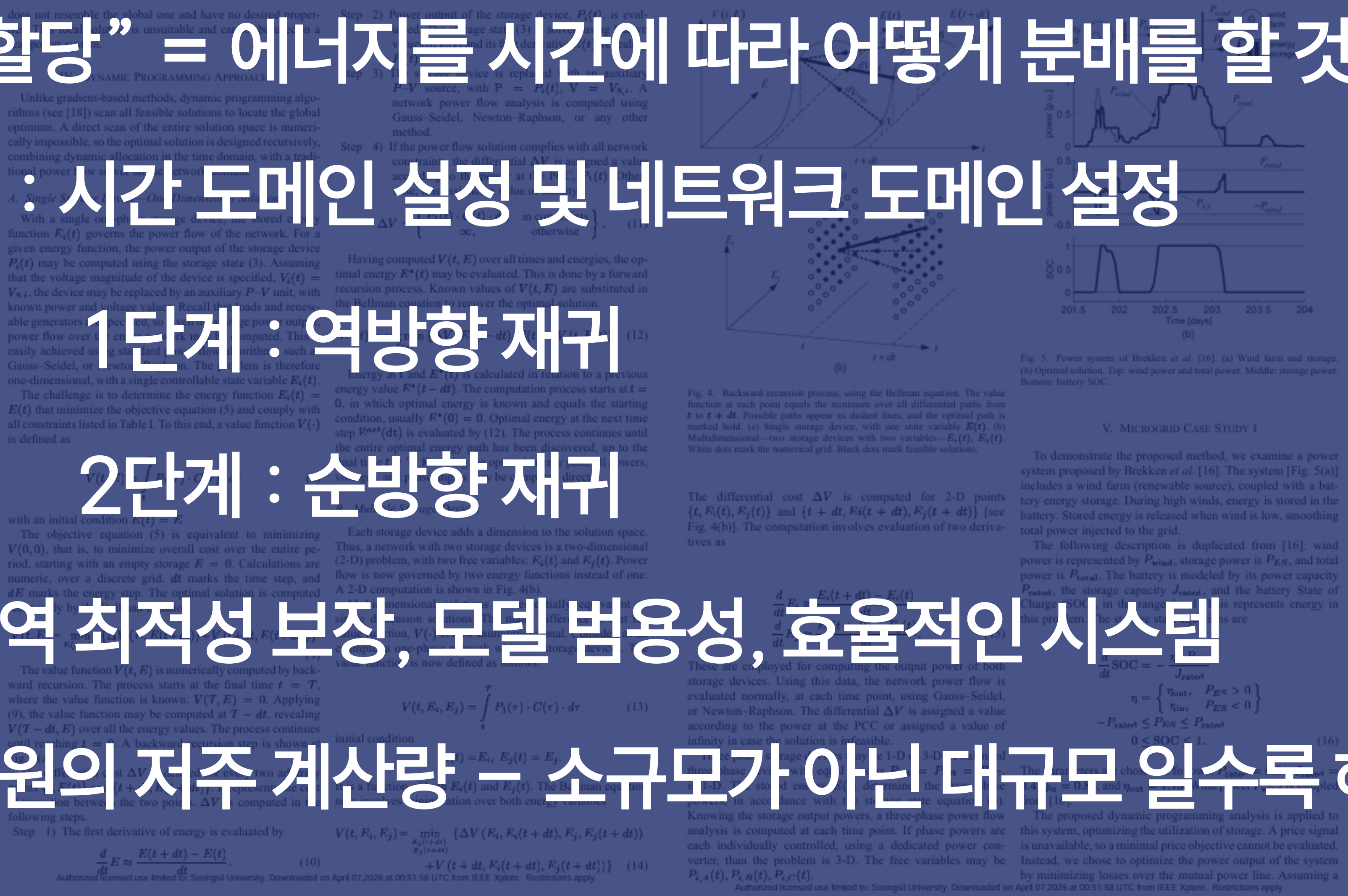
04 Dynamic Programming



발상 : “할당” = 에너지를 시간에 따라 어떻게 분배를 할 것인가

알고리즘 : 시간 도메인 설정 및 네트워크 도메인 설정

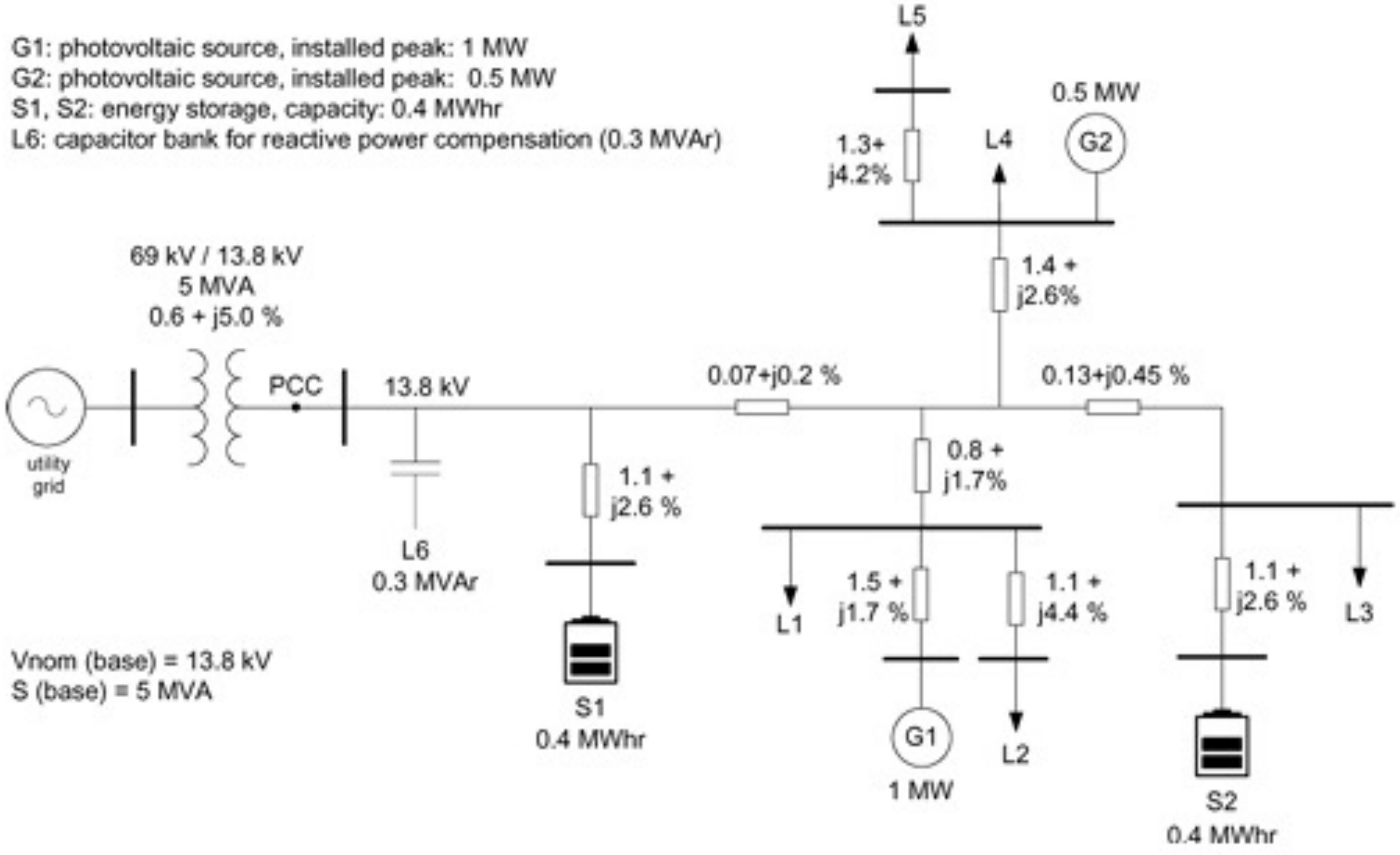
1단계 : 역방향 재귀

2단계 : 순방향 재귀

장점 : 전역 최적성 보장, 모델 범용성, 효율적인 시스템

단점 : 차원의 저주 계산량 – 소규모가 아닌 대규모 일수록 해결 힘듬

05 Experiments – 풍력 발전 출력 평활화



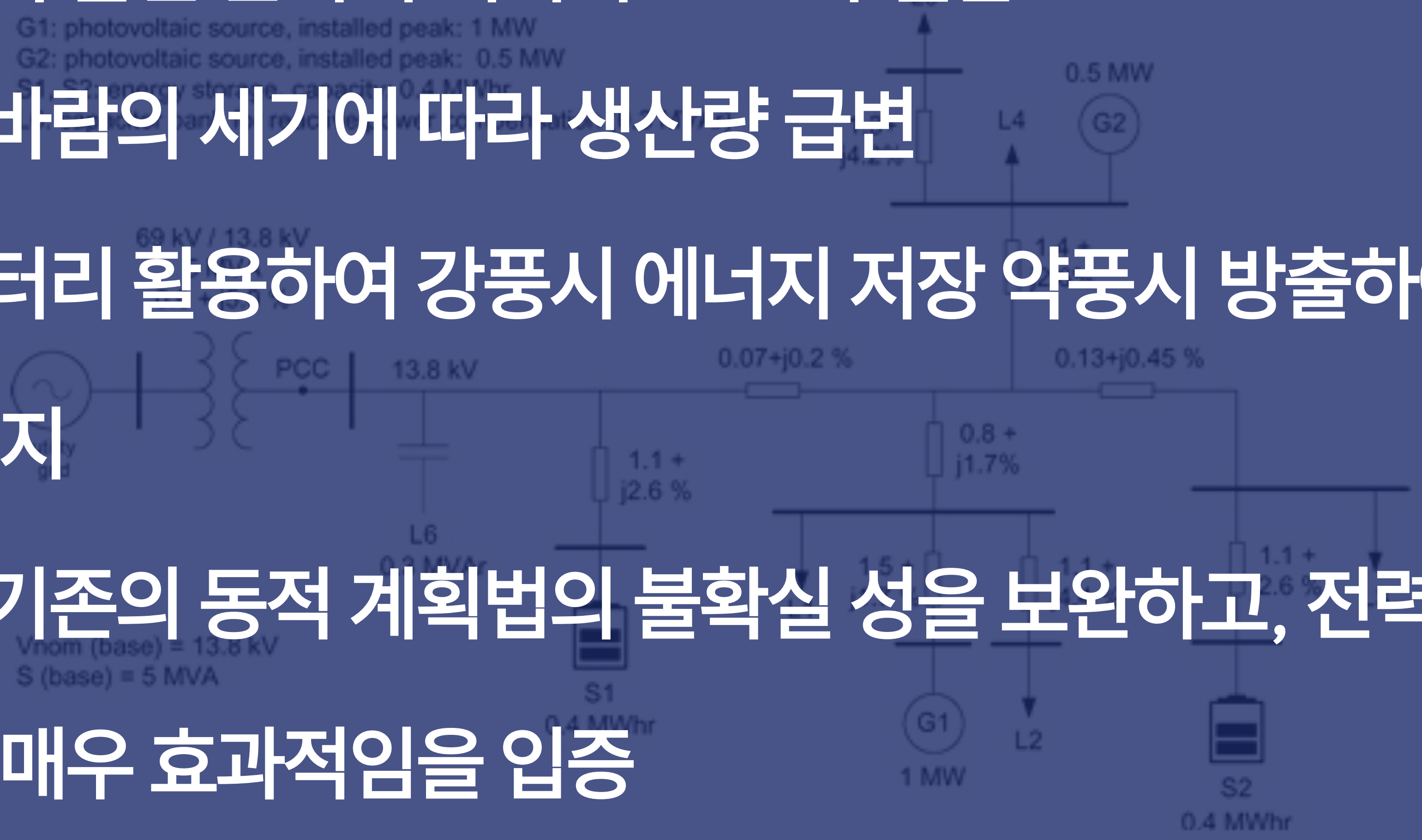
05 Experiments – 풍력 발전 출력 평활화

구성 : 풍력 발전 단지에 배터리 ESS가 결합

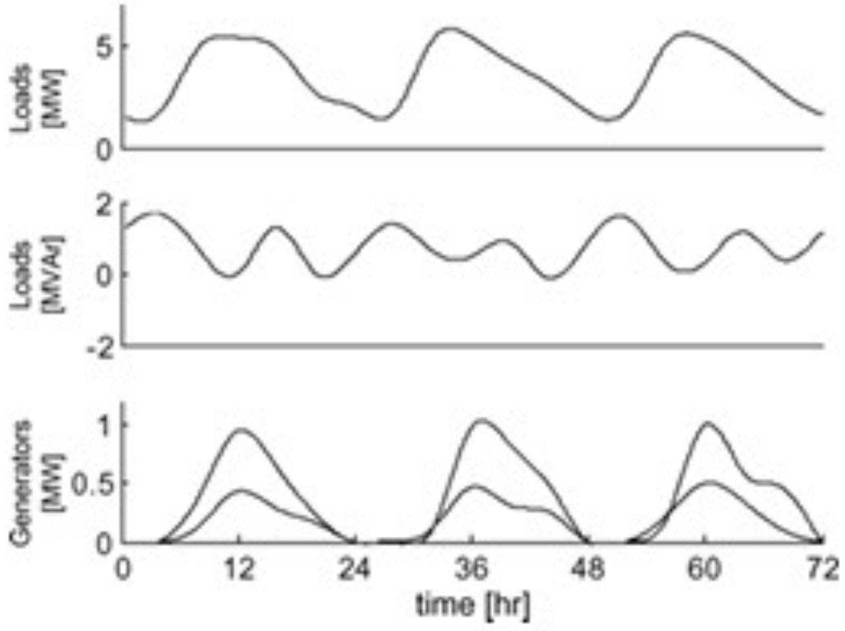
문제점 : 바람의 세기에 따라 생산량 급변

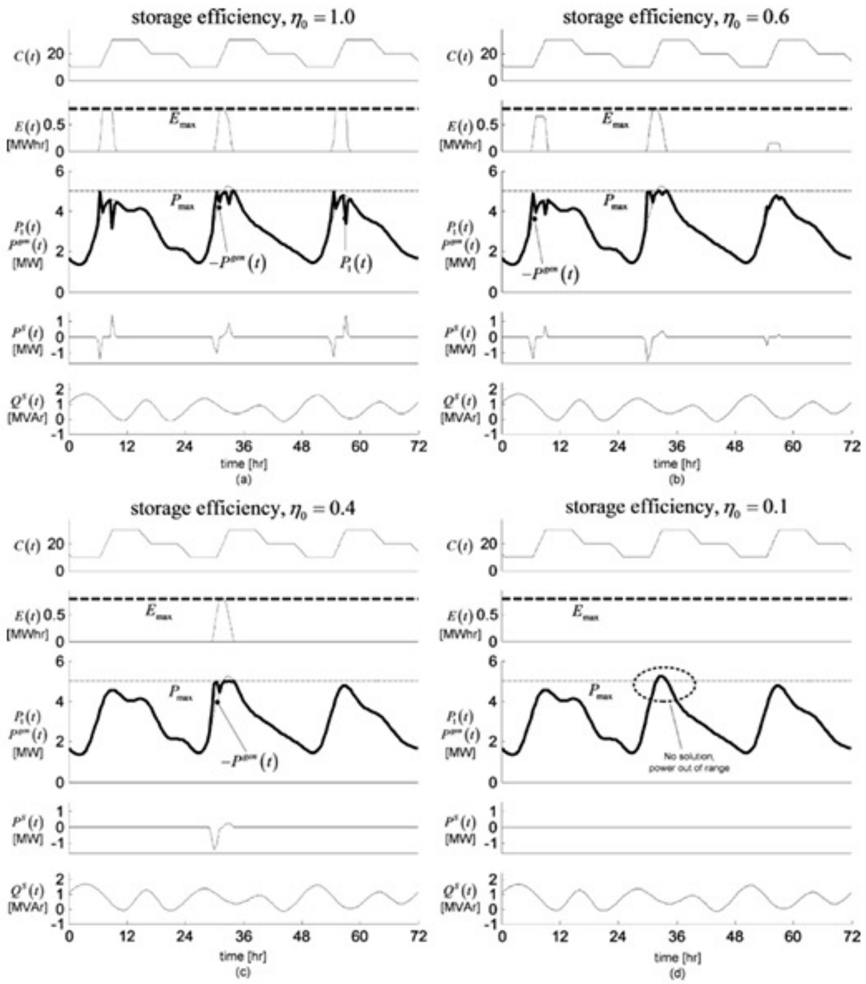
목표 : 배터리 활용하여 강풍시 에너지 저장 약풍시 방출하여 전력 출력 일정량 유지

차이점 : 기존의 동적 계획법의 불확실 성을 보완하고, 전력망의 신뢰성 높이는데 매우 효과적임을 입증

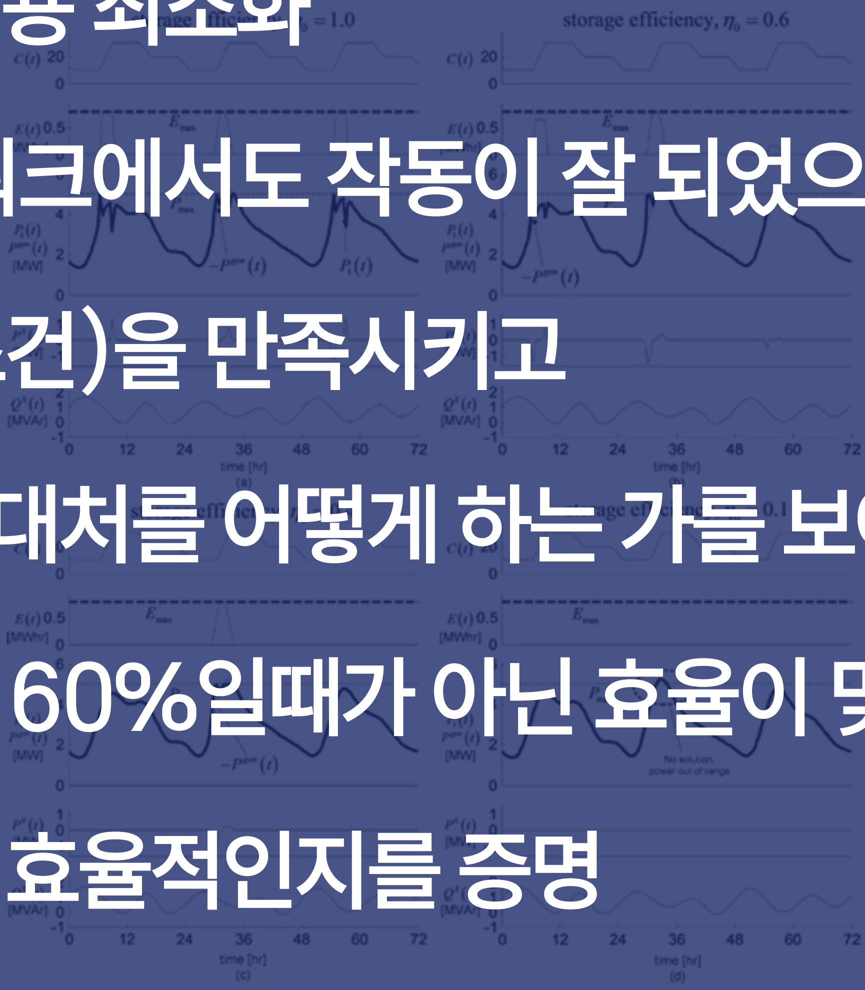


05 Experiments – 다중 네트워크 구조의 중전압 마이크로그리드





05 Experiments – 다중 네트워크 구조의 중전압 마이크로그리드



목표 : PCC에서의 총 에너지 수입 비용 최소화

실험의 결과 : 알고리즘이 다중 네트워크에서도 작동이 잘 되었으며

그리드의 안전 규칙(조건)을 만족시키고

배터리 성능에 따라서 대처를 어떻게 하는 가를 보여줌

효율이 100%일 때와 60%일때가 아닌 효율이 몇 퍼센트

이상이 나와야 ESS가 효율적인지를 증명

06 Conclusion

논문의 성과 : 계통 연계형 마이크로그리드에서 ESS의 최적 에너지 관리를 위한 알고리즘 제안 , 공통 접속점(PCC)에서의 전체 에너지 비용을 최소화하는 최적의 경로

이 논문만의 특색

1. 전역 최적해 보장
2. 범용성 및 유연성
3. 물리적 제약 준수(전압, 전류, 전력 한계)

이 논문에서의 보완할 점

차원의 저주

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Thank you

숭실대학교 전기공학부 학술 소모임 NOVA
발표자 : 이태현