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A Study on Sizing of Substation for PV With Optimized Operation of BESS

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ABSTRACT Recent development and cost down of PV(Photovoltaic) technology drive change of power
system structure. The participation of PV generation is increasing, and the size of each PV farm is getting
larger. In order to integrate large PV farms into the main grid, substation for interconnection needs to be
sized properly. Unlike substations for load and conventional generators, PV farm substation has an uneven
utilization ratio due to characteristics of solar radiation. With proper sizing method for the capacity of
the substation can reduce the building cost of facilities. A combination of an energy storage system can
further reduce the capacity of the substation. Battery energy storage system (BESS) can shift the peak
production of PV during the daytime to midnight. According to market circumstances, BESS can reduce
further construction costs by producing profit based on time difference of electric cost. For proper sizing
of substation capacity, several factors must be considered including environmental factors, market structure
and BESS in the system. In this article, a series of assessment methodology is introduced to calculate the
optimized capacity of substation and BESS for PV farm interconnection. The long-term solar radiation data
is analyzed for a given site of the PV farm. Based on market structure, the operation of BESS is optimized
to make maximum profit during operation. The iterative calculation of each step results in the calculation of
the optimized capacity of BESS and substation for given PV farm size.

INDEX TERMS BESS, PV, BESS sizing, substation, hosting capacity, machine learning classifier, neural
network fitting, REC, SMP, solar pattern.

I. INTRODUCTION

The PV(Photovoltaic) generators have variable output characteristics since solar irradiance keep changing depending on weather condition. As the penetration of PV in power system increases, the variability of generation from PV impacts on the stability of power system. The famous "Duck curve" is a representative case that shows the high penetration impact of PV generators. Some of the power systems which have high level of a PV generation ratio starting to limit the generation of PV sources in order to secure network stability [1]. Strict curtailment of renewable generations is inefficient countermeasure as penetration level of renewable generators keep increasing which are driven by several policies and environmental concern over conventional generators.

Energy storage systems such as pumped hydro storage and battery can efficiently handle variations from renewable generators. Hydro pumped storage system has been contributed to a balance between supply and demand of power system from the past and starting to gaining more popularity recently to suppress variability of renewable generators [2], [3]. Battery energy storage system(BESS) is fast and compact compare to pumped hydro storage system. Unlike a hydro pumped storage system that usually planned and built by transmission system operators, BESS tends to be installed at places adjacent to renewable sources and built by owners of generators. For renewable energy suppliers, an energy storage system can create extra profit if the electricity market is dominated by renewable generation output. For example in a market with a merit order system, the participation of renewable generators reduce system marginal price(SMP) since renewable generators have the highest priority in market [4].

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In this case, the main purpose of ESS installed by renewable energy suppliers is time-shifting of its generated power to another time zone when SMP is high. In order to reduce variation from renewable sources, transmission operator often pays extra incentives to renewable generators which have energy storage system(ESS) installed inside their facility.

Due to the high capital cost, sizing of the ESS is important in grid planning stage. Several methodologies can be found in the literature to solve the sizing problem for different objectives. In [5], sizing of storage system is considered for day-ahead forecast errors reduction and in [6] and [7] for power system frequency response support. In this case, the operation of ESS is determined for special purpose rather than being optimized cost-effectively.

In order to find economic viability of the ESS, the analysis should cover lifetime operation and capital cost for initial installation. Depending on how the operation of ESS is optimized, a daily operation of facility result in different profit and running cost. Also the operation of ESS can be varies depends on the size and energy capacity of battery system. Therefore, the operation and size of ESS should be optimized simultaneously.

Several studies have focused on the development of BESS control strategy to maximize system profit. Scheduling of ESS is studied in [8] with PV generators integrated into the grid. The utilization of ESS with PV generators is proved to be worthy in cost-benefit analysis, however, the sizing of ESS is not covered. When sizing of ESS is considered, operation of ESS are determined based on heuristic rules, to minimize the complexity of optimization problem. In [9], [10], sequential, multi-stage co-optimization of energy storage sizing and control strategy of PV plant is proposed considering market conditions.

Little attention has been paid for sizing of ESS for grid expansion purpose. Several authors have focused on considering ESS for short-term and long-term grid planning. In [11] and [12] utilize ESS for short-term planning. In long-term planning, [13] proposed a multi-stage model to co-optimise capital cost and operation of ESS for grid expansion with renewable integration.

In transmission or distribution grid where PV installation has concentrated, the connection of new PV plants often limited to the remaining hosting capacity of the interconnecting grid. In this case, the transmission network or substation needs to be expanded to meet the surplus loading on facilities. An ESS can be installed to delay such upgrade or completely substitute traditional upgrading procedure. The economic analysis should be preceded when considering ESS for grid expansion. In general, following circumstances can make ESS more economical solutions: When short-term overload appears and application of conventional renovation method is restricted [14]. The economical expansion planning analysis of PV system with ESS has been addressed in the literature [15], [16]. When connection of PV plants result in overloading at substation, ESS can comprises a promising and cost effective solution [17].

The required capacity of the transformer can be reduced by detouring overflow of output from PV generators to ESS and discharge later [18], [19]. During this operation, ESS status is determined and the controller verifies that overflow from the PV generator is acceptable to BESS which is limited by the state of charge(SOC) and capacity of the power conversion system.

This control strategy is beneficial for PV system operators when the expansion of PV plants is limited due to deferred substation upgrades. The capacity of PV plants can be increased without considering the remaining hosting capacity of the interconnected grid, while no grid reinforcement is required. The sizing of ESS, in this case, require additional consideration of PV capacity and solar irradiance pattern in specific area. Very few researches are conducted focusing on sizing of ESS for PV integration to grid using the above control strategy [20], and yet did not considered the PV plants sizing in a range beyond substation limit. In [21], one-year solar irradiance pattern are considered for ESS sizing, however, ESS is not considered for further grid expansion with simultaneous PV sizing.

In this article, the method of sizing a PV and BESS is proposed when the hosting capacity of grid is limited. The long term solar irradiance data is analyzed and the operation of BESS is optimized for maximum profit under market conditions with incentives for BESS installation in PV plant. For each scenario of PV generation, active expansion planning method is applied with BESS operates to restrain overflow to the substation. During the optimization process, one-year solar pattern is analyzed and operation of BESS is constrained for grid expansion purpose.

The contribution of this article is as follows.
- Operation of BESS is optimized for one-year solar irradiance scenario and market condition without creating overflow to the interconnected grid
- Simultaneously optimize size of ESS and PV plant under optimized operation and energy management for battery lifetime

Section II presents the preparation of solar irradiance data and system marginal price. Correlation between market condition and renewable generation output is determined and representative scenarios are prepared for following optimization process. Section III proposed the sizing method of substation considering the optimized operation of BESS under specific market conditions. Section IV presents the result of simulation and discussions of the utilization of the proposed method and Section V concludes.

II. SOLAR IRRADIANCE DATA WITH SYSTEM MARGINAL PRICE

Solar irradiance data is important in the planning of PV generators as the total production of plants can be varied by it. In order to assess possible generation output from PV generators at a specific area, at least more than one year of irradiance data is required since the change of weather and temperature are critical factors for solar irradiance. The
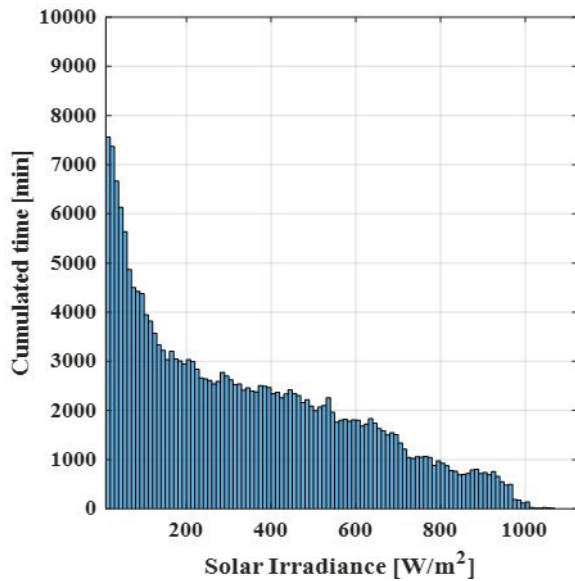
FIGURE 1. Solar irradiance histogram of Mokpo city, Korea.

TABLE 1. Machine Learning Classification Result of PV Patterns.

Intensity	Cloud Pattern	Classified Count
Moderate	SN	73
	SN_NO	7
	CL_SN	11
	SN_CL	15
	CL	19
Strong	SN	62
	SN_NO	16
	CL_SN	7
	SN_CL	9
	CL	15
Weak	SN	52
	SN_NO	18
	CL_SN	10
	SN_CL	10
	CL	41

histogram of irradiance data at Mokpo city in Korea is shown in Fig. 1. As depicted in the histogram, the operation of PV generators near rated capacity is intermittent compare to other operation range. Thus, even with a small capacity of BESS in the system, the required transformer capacity can be reduced significantly. In the same manner, the maximum capacity of PV generators can be increased that the capacity of transformers for interconnection is limited.

A. SOLAR IRRADIANCE PATTERN CLASSIFICATION

Before conducting the optimization process, a year-long PV scenario should be classified into several types of patterns in order to reduce computation time. If a total amount of solar irradiance is preserved after classification, the result of optimization process with classified patterns will coincide with the result with original patterns. In [22], solar irradiance pattern can be classified into 5 representative patterns that determined by block patterns of solar irradiance by cloud. In addition to block patterns by cloud, seasonal change of irradiance pattern also needs to be considered for classification. Solar irradiance can be affected by the seasonal change which is mainly influenced by the orbit of the sun. Three stages of solar irradiance are considered to reflect a seasonal change of irradiance strength. This assumption is feasible in a place where a distinctive change of 4 seasons exists that have 3 stages of solar irradiance strength (winter, summer, and in-between seasons). It should be noted that each season also has a difference in sunset and sunrise time. Therefore, 15 irradiance pattern is introduced for classification of given one-year data of solar irradiance.

Classification of solar irradiance patterns can be conducted using a self-trained machine learning application. In solar irradiance pattern classification, distinctive parameters can be easily identified such as the ratio of maximum solar irradiance and sunset time. [23] In order to make a classifier, 15%

of data from irradiance records of Mokpo city is used for training by support vector machine(SVM). The given data contain one-year records of irradiance at Mokpo city in the southern part of Korea which has adequate weather condition for PV generation. The selection of classifier for the data analyzation is focused on accuracy and error of the total irradiance amount between classified and original scenarios. Table 1 shows result of classification of given irradiance data. Each of categorized data name stands for strengths(S = Strong, M = Moderate, W = Weak) and patterns (SN = sunny, CL = cloudy, NO = noise (frequent small clouds)).

B. BUILDING SMP SCENARIO BASED ON IRRADIANCE PATTERN

The main purpose of BESS operation in PV plant is the time-shifting of PV output to a different period when SMP is high. The difference between the highest and lowest SMP is an important factor to calculate possible BESS profit. As renewable generators are increasing in power system, SMP of the system can change since fuel price of renewable generators are not considered in conventional market system [24].

Thus, the selection of valid SMP pattern data for each irradiance scenario is important to ensure the logical validity of the following optimization process. SMP data is gathered from the Korean electricity market that corresponding to the same periods of irradiance data. Patterns of SMP can be varied from day to day and increase the complexity of the optimization problem. The same approach of pattern classification can be applied to SMP patterns and yet this method can also multiply the number of scenarios exponentially. For simplification, assumption can be made based on the correlation between SMP patterns and classified irradiance pattern.

As depicted in Fig. 2 most SMP patterns shows the highest SMP at 13 o'clock and lowest at 5 o'clock. And the gap between the maximum and minimum price is concentrated near 10$/kWh. Contrary to 'S_SN' case, 'W_SN' category have SMP patterns with different peak SMP time as shown
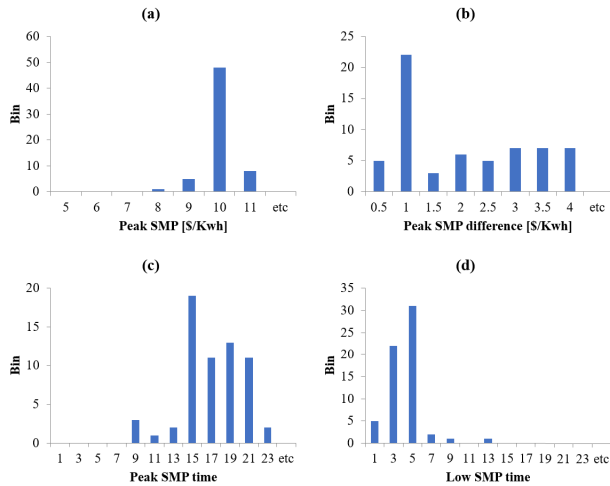
FIGURE 2. SMP ptatterns histogram 'S_SN' category (a) peak SMP in $/kWh (b) Min Max gap of SMP $/kWh (c) highest SMP time (d) lowest SMP time.
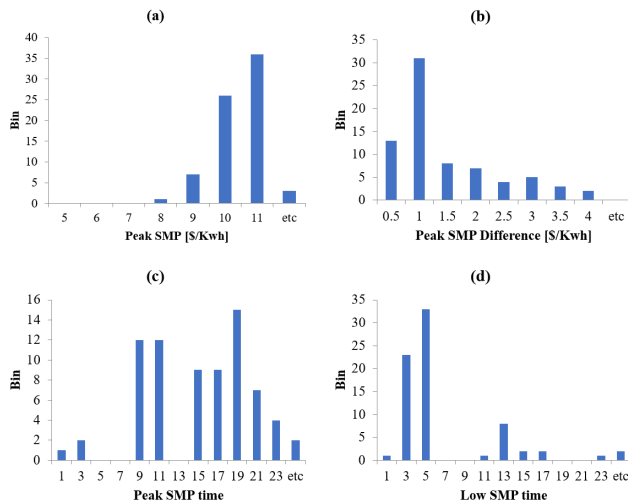

FIGURE 3. SMP ptatterns histogram 'W_SN' category (a) peak SMP in $/kWh (b) Min Max gap of SMP $/kWh (c) highest SMP time (d) lowest SMP time.

in Fig. 3. This phenomenon can be explained in a way that the solar irradiation pattern is closely related to seasonal characteristics and the change of SMP pattern also can be explained in seasonal differences. As mentioned earlier in [24], this correlation becomes more significant as the penetration level of renewable generators increases. The meteorological correlation between each PV plants in the large terrestrial area is relatively high compare to other renewable sources. The concentration of PV generation at a specific time range leads to the 'Duck curve' phenomena in the power system when there is a high level of PV penetration exists.

For group of SMP patterns that categorized by corresponding PV patterns, representative case is composed by Neural Network fitting. 70% of data is used for training while rest of them are used for validating and testing. Representative patterns of SMP for 'S_SN' and 'W_SN' categories are shown in Fig. 4.
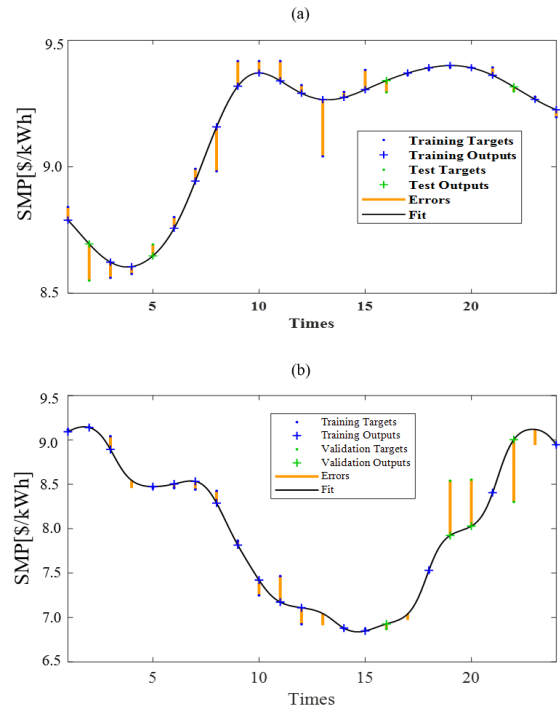

FIGURE 4. Representative patterns of SMP (a) 'S_SN' (b) 'W_SN'.

III. PLANNING OF PV SYSTEM WITH SUBSTATION

Planning of PV system starts with the sizing of BESS capacity for maximum profit. In this process market structure is a dominant factor to determine the size of adequate BESS for PV. If the penetration level of renewable generators is low and SMP is stable, BESS installation won't create large enough profits to cover the capital cost of the entire system. As the level of penetration is increase and transmission system operator values storage devices in order to decrease variability from renewable sources, BESS can have a financial advantage. When the SMP gap between maximum and minimum point increases, the PV system with BESS has more profit compare to plants with PV only. In some cases, transmission system operator often gives incentives to plants with BESS or limit generation from plants without a storage system. In Korea, PV plants with BESS installed in generating sites can receive profit in addition to sales to the electricity market by SMP [25]. The amount of incentives is proportional to the total production of power that discharged from BESS only, and BESS can only charge from powers of PV sources.

Transformer capacity is not a crucial factor for PV system planning as it's building cost is relatively low compare to PV and ESS devices. Furthermore, the capacity of the transformer is often limited by transmission system operators depend on the hosting capacity of the interconnecting grid. For instance, the size of PV capacity is limited by a remaining capacity of transformers when connecting the PV system to an existing substation. As mentioned earlier, the utilization ratio of PV generator is less than 20% and rarely operate near rated capacity of devices. If BESS can charge overflow from PV generators and PV controls it's output considering
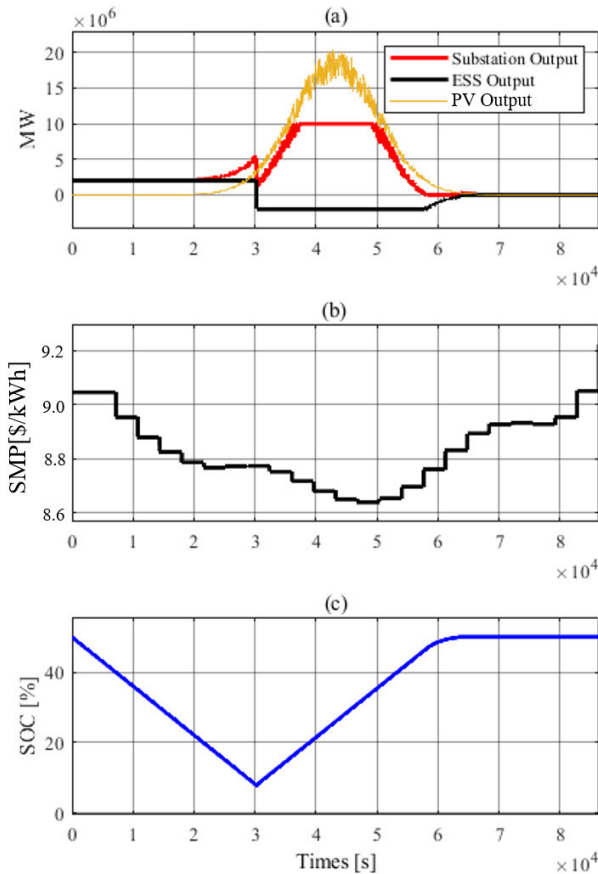
FIGURE 5. Operation of BESS for PV interconnection to small transformers (a) Active power production from each devices (b) SMP patterns (c) SOC status of ESS.

maximum limits of substation's capacity, limit of the PV capacity by grid condition can be increased. Fig. 6 shows the operation strategy of PV and BESS at substation with low capacity.

When suppression of over-generation by ESS is applicable to an optimization problem, sizing of PV system for maximum profit should take several factors into consideration since the maximum range of PV capacity is no longer limited by the capacity of interconnecting transformers. It is surmisable that installing PV and ESS beyond the transformer capacity limit can still increase total profit when proper charging and discharging operation is conducted. In order to verify this assumption and find the optimal size and combination of facilities in the PV system, the following method is proposed. During the normal operating condition, BESS is scheduled to maximize profit by charging and discharging at different periods. To solve the optimization problem in a simple manner, the cycle between charge and discharge operation of BESS can be limited to 2 times in a single day. This assumption is valid considering the fact that most manufacturers of BESS guarantee operating capacity of devices under limited charge/discharge cycle condition. This constraint can make optimization problem much easier to solve by maximizing the life expectancy of devices. Fig. 5 shows simulation results
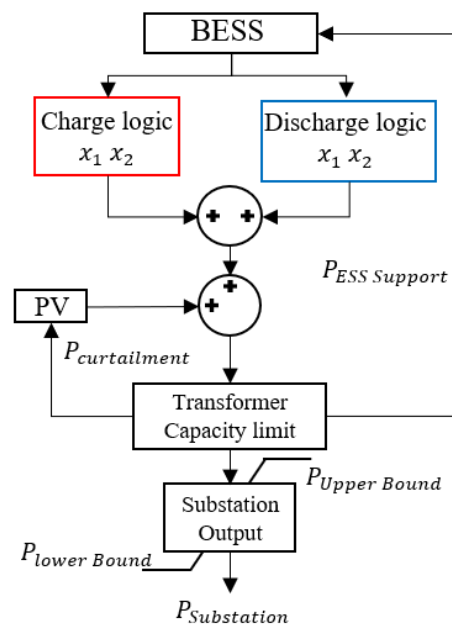

FIGURE 6. Operation of BESS with PV plants for output suppression.

after the optimization process with a 40MW PV plant interconnected to 10MW substations. In this case, BESS have 2MW PCS and 40MWh batteries. For the given SMP pattern, BESS discharge until dawn since SMP have the highest point at the beginning of the day.

To identify the optimal size of BESS and substations for the PV system, a number of combinations should be considered. As the charge operation of BESS is limited to outputs from PV generators, it is inefficient that PCS of ESS have a larger capacity than those of PV generators. Thus, the range of PCS system capacity should be smaller than the capacity of PV generators. The general approach of sizing batteries for incentives is charging entire production from PV plants during day time and discharge to market to receive maximum incentives. In Korea, average production from a 1MW PV generator is 4-5MWh per day and under subsidy for ESS installation, the empirical optimum size of ESS is around 3.77MWh [26] with 1MW PCS. This is corresponding to batteries with 0.26 C-rate value and thus, for the optimization process, a number of scenarios are prepared to include cases that have C-rate value of 0.25.

Fig. 7 shows overall procedure of assessing combinations of device's capacity. First, a number of values for capacity of each devies are prepared. This value can be any numbers, however, they needs to be carefully selected since increase of each cases multiply total number of scenarios that needs to be optimized. For instance, when N cases of PV capacity, M cases of BESS capacity and L cases of transformer capacity are prepared as shown in Fig.7. For each set of parameters, 15 solar irradiance pattern is applied and determine outputs from PV generators. This will leads to N*M*L*15 cases that needs to be opt As depicted in Fig. 6, each scenario result in corresponding daily profit created by selling to electricity
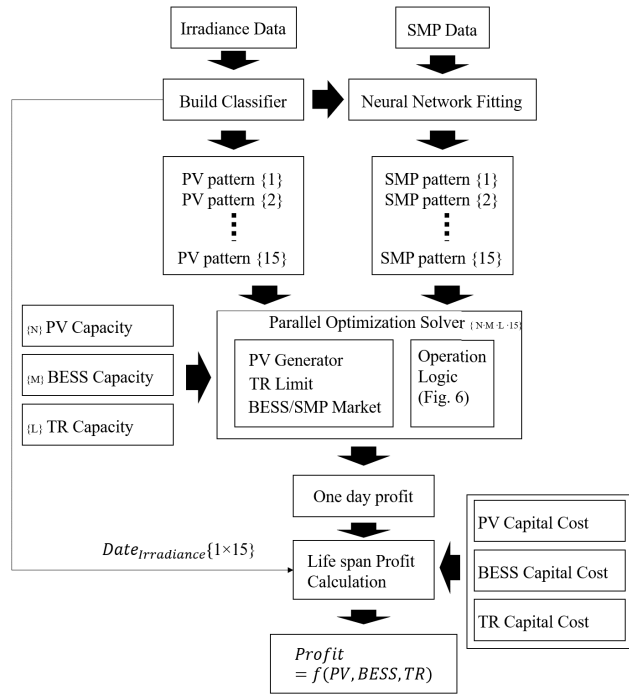
FIGURE 7. Optimization process to calculate life span profit.

FIGURE 8. Optimized profit for 10MW PV plants with 10MW transformers.

market at given SMP patterns. By setting daily profit as objective functions for optimization process, it can be calculated in (1) as

$$F = (P_{pv} + P_{ESS}) * SMP + P_{ESS_{disch}} * C_{incentives} \quad (1)$$

where P_{pv} is output generated from PV generators and P_{ESS} is output from BESS. P_{BESS} can have positive and negative values according to operation mode between charge and discharge. $C_{incentives}$ is additional incentives from transmission system operators that can only be applied to production from discharge of BESS. Variables for optimization process is modeled as follows.

$$0 \leq x_1, x_2, x_3, x_4 \leq 24 \quad (2)$$

where x_1 and x_3 each represents for charge and discharge time while x_2 and x_4 are duration of operation. P_{ESS} from (1) can be explained by using (2) as

$$P_{ESS} = P_{ESS_{char}} + P_{ESS_{disch}} \quad (3)$$

$$P_{ESS_{char}}(t) = \begin{cases} 0 & t < x_1 - x_2 \\ 1 & x_1 - x_2 < t < x_1 + x_2 \\ 0 & t > x_1 + x_2 \end{cases} \quad (4)$$

$$P_{ESS_{dischar}}(t) = \begin{cases} 0 & t < x_3 - x_4 \\ -1 & x_3 - x_4 < t < x_3 + x_4 \\ 0 & t > x_3 + x_4 \end{cases} \quad (5)$$

where $P_{ESS_{disch}}$ and $P_{ESS_{char}}$ determine time and duration of IEESS operation. The optimization constraints are related to SOC status of BESS. Operating points of BESS have
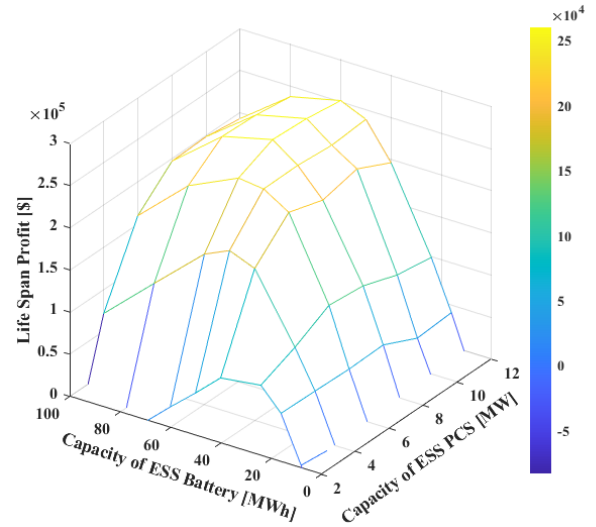
limited range of SOC to preserve discharge characteristics of batteries. Initial and end value of SOC should be set to identical so as to precisely reflect capacity of BESS to optimization result. It should be noted that result of optimization data will be utilized to assess one-year operation profit of given systems. If SOC status constrain is violated, result of assessment can change drastically. Constraint are modeled as follows:

$$SOC_{lower_{limit}} \leq SOC(t) \leq SOC_{upper_{limit}} \quad (6)$$

$$SOC_{initial} = SOC_{end} \quad (7)$$

where $SOC_{lower_{limit}}$ and $SOC_{upper_{limit}}$ is SOC limits of given BESS system. In order to simplify optimization process, given optimizing model can be split into two independent problems by transforming (3) into (8).

$$P_{ESS} = P_{ESS_{char}} * (1 + P_{ESS_{disch}}) + P_{ESS_{disch}} \quad (8)$$

By using (8), charging and discharging operation became independent and discharge operation have priority over charge operation. Two stage optimization process starts with optimization of design variables x_1 and x_2 with new constrain modeled as (9) in replacement of (7).

$$SOC_{end} = SOC_{upper_{limit}} \quad (9)$$

After design variables x_1 and x_2 are optimized, rest of design parameters are optimized by using constrain (6) and (7). As a result, each combination of scenario has 15 optimized daily profit calculated by (1). Using number of dates in Table 1. yearly operation profit can be calculated. Final assessment of each scenario requires capital cost of each devices. At this stage, life expectancy of PV plants and BESS must be included. Life expectancy may vary according to manufactures of devices and operation strategy during optimization process.
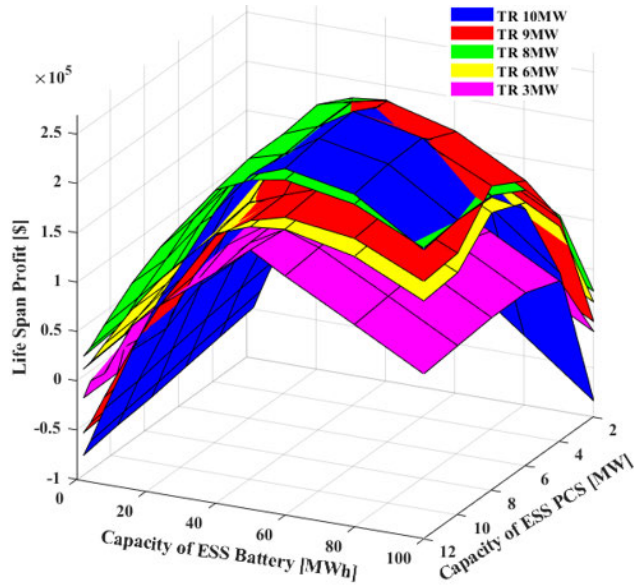
FIGURE 9. Optimized profit for 10MW PV plants with different transformer capacity.

TABLE 2. Parameters for Optimization.

Incentives (\$/MWh)	PV plants capital cost [\$]			
	Energy capacity (\$/kWh)	Power conversion systems(PCS) (\$/kW)	Transformer price (\$/kW)	PV plant price (\$/kW)
60	288	271	10	170

IV. SIMULATION AND DISCUSSION

For simulation, solar irradiance data from Mokpo city in Korea is used as described in section II and corresponding data of system marginal price is collected from Korean Power Exchange. The PV plants are designed to have 90% efficiency and a lithium-ion battery is considered for BESS since it has long life cycle in a partial SOC cycling regime at various rates [27]. For the optimization process, the total capital cost of the lithium-ion battery system is calculated per kW and kWh values. An analysis from literature and technical reports [28], [29] stated the range of capital cost of the lithium-ion battery is \$223 to \$323 per kWh average. In this article, the estimated capital cost value for the year 2018 is used in [27]. The overall service life expectancy that considered in the optimization process is 10 years as in [27]. Detailed simulation parameters are shown in Table 2 and result of simulation can be found in Fig. 8 when using 10MW transformer to integrate 10MW PV facilities. It can be found out from the result of simulation that optimized combination of ESS for 10MW PV plants is 8MW PCS system with 60MWh batteries. Capacities above this point starting to show decreased profit due to higher capital cost and a poor utilization ratio of ESS.

A. SIZING OF TRANSFORMERS FOR PV PLANTS

For a given PV plants, assessment of influence by transformer can be conducted using proposed method. As depicted
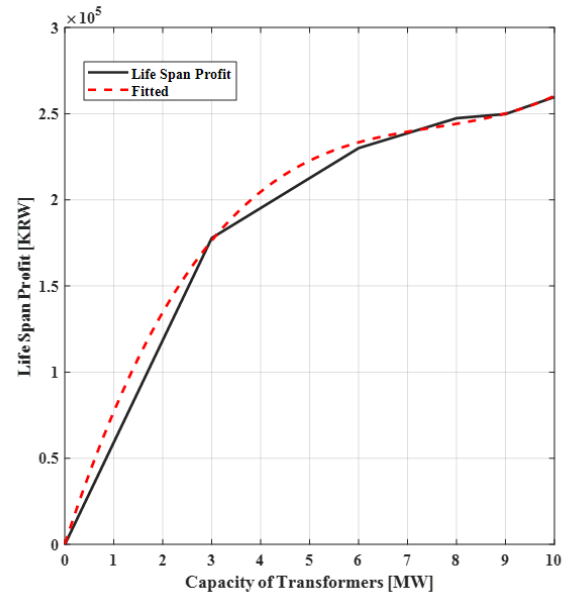

FIGURE 10. Life span profit according to capacity of transformers.
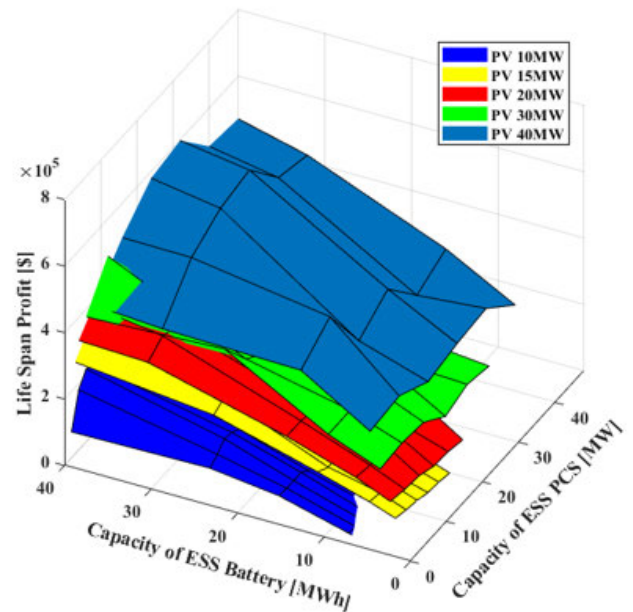

FIGURE 11. Optimized profit for 10MW substations with different PV capacity: case for (ESS Battery < 40[MWh]).

in Fig. 6, operation limit of PV plants is capacity of interconnected transformers. If power flow from PV generators and ESS exceed transformer limits, both ESS and PV trying to suppress it. Fig. 9 shows optimization result by using different transformer capacity. Life span profit of cases with small transformer shows lower output although the capital cost of transformer has also reduced. In fact, when transformer capacity reduced from 10MW to 9MW, life span profit only reduced to 0.7% although the reduction of transformer cost is smaller compare to this value. The tendency of decrease profit is shown in Fig. 10. By setting life span profit to zero for transformers with 0MW case, one can expect decreasing ratio of profit as transformer size become smaller.
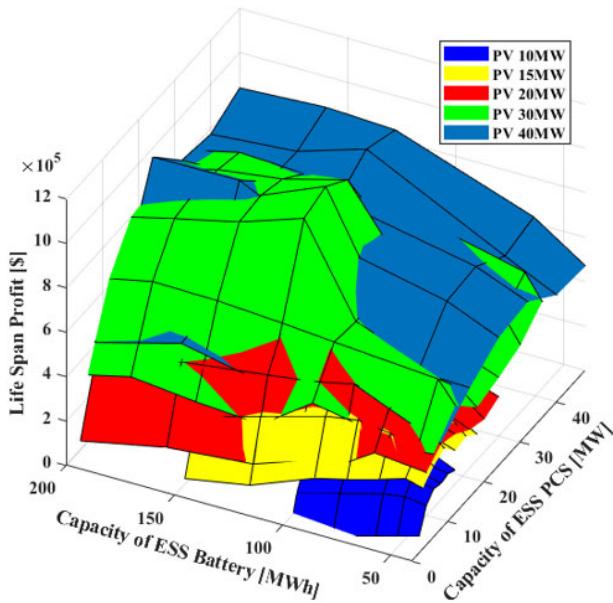
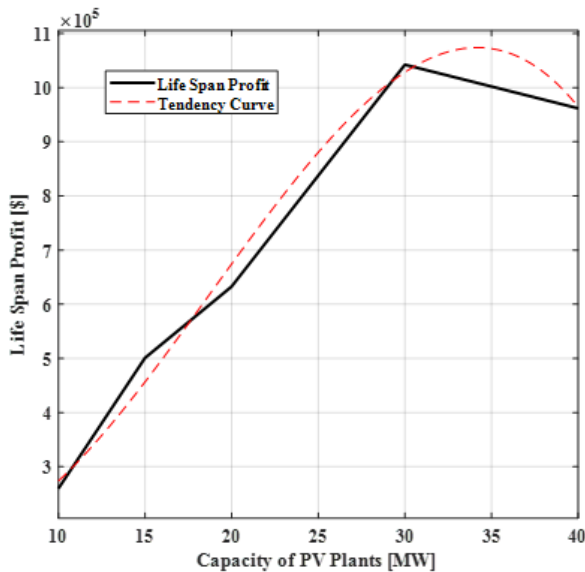**FIGURE 12.** Optimized profit for 10MW substations with different PV capacity: case for (ESS Battery > 40[MWh]).

FIGURE 13. Life span profit according to capacity of PV plants.

B. SIZING OF PV PLANTS FOR TRANSFORMERS

In case of interconnecting PV plants to transformers with limited capacity margins, proposed assessment procedure can be applied. Set of simulations is prepared with constant transformer capacity, 10MW. As capacity of PV plants change, ESS capacity range also needs to change on contrary to former cases.

Result of simulation is shown in Fig. 11 and Fig. 12. In scenario with low ESS battery capacity, increase of PV generation capacity does not leads to total profit increase. In some cases, large PV integration result in budget deficit. Addition of PV capacity starting to gain profit when installed capacity of ESS battery is 3-4 times larger than PV capacity. By doing so, PV plants can store surplus power while flow

TABLE 3. Optimized Parameters for 10MW Substation Interconnection.

	Transformer capacity [MW]	PV [MW]	PCS [MW]	ESS [MWh]	Total profit [10k$]
Case 1	10	10	8	60	25.97
Case 2	10	15	12	90	50.01
Case 3	10	20	16	120	63.28
Case 4	**10**	**30**	**24**	**120**	**104.23**
Case 5	10	40	24	160	96.18

through substation is limited. Table 3 shows optimized sizing of ESS for five cases of PV capacity. Total profit from case 4 shows the highest total profit value. Fig. 13 shows relationship between PV capacity and total profit of case 1 to 5. It can be estimated from the graph that interconnection of PV plants that have capacity between 30 and 35MW can leads to most profitable combination with 10MW transformers.

V. CONCLUSION

In this article, detailed analysis has conducted to determine adequate capacity of PV plants when interconnected with substations with limited capacity and vice versa. During process of assessment, BESS is installed to achieve three operation purpose. First, BESS operate to extend capacity limit by transformer to PV plants. Second, BESS can achieve additional profit by time-shifting generation of PV plants from low SMP period to high SMP period. And third purpose of BESS installation is to get incentives from transmission system operators. The contribution of this article is proposing procedure to find optimized capacity of PV and ESS while optimizing operation of ESS for profit without violating limit of interconnecting transformer. Complex optimization problems with multiple variables are redesigned into a series of easier optimization problems that can be assessed step by step.

As a result of proposed assessment procedure, profitability of PV plants are verified under limited interconnecting condition. As capital cost of storage system and PV plants expected to decrease in future, this type of analysis will became more relevant. It also should be noted that PV and ESS system with suppressed output(For instance, in case 4 at Table 3) have significantly decreased variability compare to stand alone PV system.

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