An Optimal Sizing and Economic Evaluation of VPL to Improve Hosting Capacity of Renewable Energy

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재생에너지 수용능력 향상을 위한 VPL의 최적 용량 산정 및 경제성 평가

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Abstract

Recently, the integration of renewable energy sources (RES) into distribution systems has become a global challenge. This is due to the frequent overvoltage problems and limited hosting capacity. The usual solutions are to build a new feeders, transformers or substations. However, existing solutions are associated with enormous costs and require long construction times. Therefore, this paper presents the concept of Virtual Power Line (VPL), which increases the renewable hosting capacity without having to expand the physical infrastructure of the distribution systems. And also, the small, medium and large VPL models are categorized according to the degree of penetration of renewable energy. In addition, an economic evaluation method is applied based on cost and benefit elements, deferred infrastructure investments, and the pricing of hosting-capacity. From the the simulation results of the three models (small, medium and large scale), the optimally sized VPL devices can effectively keep customer's voltage within allowable limits while achieving shorter payback periods compared to conventional reinforcement. Therefore, it is confirmed that the VPL device is both a technically feasible and economical solution for distribution systems with a high proportion of renewable energy sources.

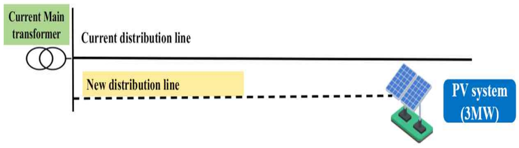
1. Introduction

The capacity of renewable energy sources connected to the distribution grid has increased rapidly every year in line with the global Green New Deal and RE3020 policy. In particular, the voltage of customers often violates the allowable voltage limit (207[V]~233[V]) due to the rapid increase of renewable energy sources during the day. To solve these problems, the installation of additional power supply systems has been proposed. However, due to the high construction costs and long construction times, there is a need for research to reduce the investment costs of power supply systems. Therefore, this paper presents an introduction model, which is a technology for operating a virtual power line to improve the hosting capacity of renewable energy sources without additional expansion of power grid infrastructure, and proposes a feasibility evaluation method for economic implementation. Based on the implementation model of the VPL device and the economic evaluation model, it is confirmed that selecting an optimal capacity for the VPL device model is more effective than investing in the existing power grid infrastructure.

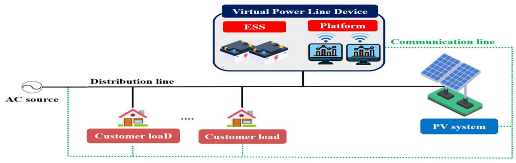
2. Introduction models of VPL device

2.1 Small-scale model

Based on the above mentioned classification of installed capacity for renewable energy sources, small-scale introduction model of VPL device is shown in Fig. 1. Where, Fig. 1(a) shows the conventional model which new overhead distribution line (D/L) and power poles are added on existing power infrastructure when small scale renewable energy sources (3[MW]) are installed in distribution system which means that the utility has to invest heavily in low utilization equipment to accommodate renewable energy sources. However, Fig. 1(b) is a new model of VPL device that can efficiently manage the distribution grid by charging and discharging in ESS located on existing distribution line, without additional investment in power grid infrastructure.



(a) conventional model

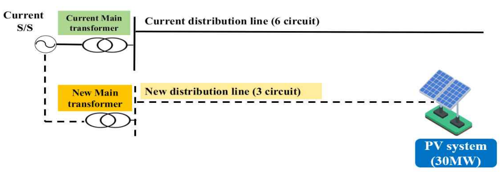


(b) new model in VPL device

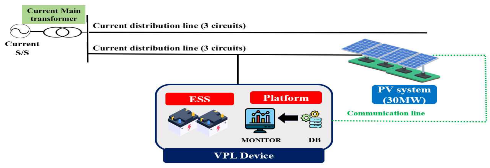
[Fig. 1] Small-scale introduction model in VPL device

2.2 Medium-scale model

Based on the above mentioned classification of the installed capacity for renewable energy sources, the medium-scale introduction model of the VPL device is designed as shown in Fig. 2. Where, Fig. 2(a) shows the conventional model in which a new main transformer of 45/60[MVA] is installed in a substation, including 3-circuits overhead line and power poles on the existing power infrastructure when medium-scale (30[MW]) renewable energy sources are installed in the distribution system which means that the power utility needs to invest heavily in low utilization equipment to accommodate renewable energy sources. Fig. 2(b) is new medium-scale model of a VPL device to efficiently control the distribution system through charging and discharging operations in ESS located on an existing 3-circuits distribution line, without additional investment in power grid infrastructure.



(a) conventional model

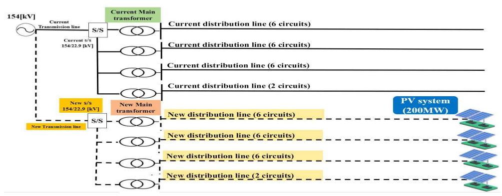


(b) new model in VPL device

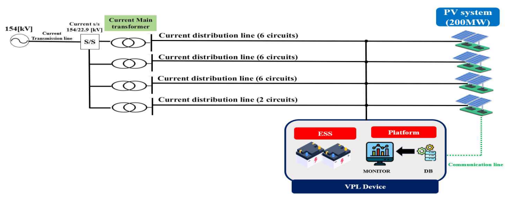
[Fig. 2] Medium-scale introduction model in VPL device

2.3 Large-scale model

Based on the above-mentioned classification of installed capacity for renewable energy sources mentioned above, the large-scale introduction model of the VPL device is configured as shown in Fig. 3. Where, Fig. 3(a) shows the conventional model in which a new underground transmission line, a substation with 4 main transformers, an overhead line with 20 circuits and numerous power poles are added on the top of the existing power infrastructure, which means that the utility has to invest a lot of equipment with low capacity utilization to accommodate large-scale renewable energy sources. However, Fig. 3(b) is a new large-scale model of a VPL device to efficiently control the distribution system by charging and discharging in ESS located on an existing 20 circuits distribution line, without additional investment in power grid infrastructure.



(a) conventional model



(b) new model in VPL device

[Fig. 3] Large-scale introduction model in VPL device

3. Economic evaluation method for VPL device

3.1 Cost elements

The cost elements for the implementation of VPL device consists of construction cost as well as maintenance and operating costs. The construction cost of the VPL device consists of the costs of ESS and the platform as shown in Equation (1). The operating and maintenance costs calculated using a constant percentage of the initial construction costs of the VPL device as shown in Equation (2), taking into account the annual inflation rate.

$$C_{VPL} = [(C_{PCS} \cdot Q_{PCS}) + (C_{bat} \cdot Q_{bat})] \cdot (1+\alpha) + \beta \quad (1)$$

$$C_{op} = \sum_{i=1}^{n} [C_{ESS} \cdot r_{op} \cdot (1 + r_{inf}(i))^{i-1}] \quad (2)$$

Where, C_{VPL}: construction cost of VPL(won/kWh), C_{PCS}: construction cost of PCS system (won / kW), Q_{PCS}: capacity of PCS system(kW), C_{bat}: construction cost of battery system (won / kWh), Q_{bat}: capacity of battery system(kWh), α: rate of VPL platform(%), β: replacement cost of battery(won/kWh), C_{ESS}: total construction cost of ESS for VPL(won), C_{op}: total operating cost(won), $r_{inf}(i)$: inflation rate(%), i: year of economic evalution, n: total year

3.2 Benefit elements

3.2.1 Improving the benefits of hosting capacity for renewable energy sources

The benefit of hosting capacity for renewable energy sources is composed of the system marginal price (SMP), the renewable energy certificate (REC) and the carbon emission reduction credit based on the production amount of renewable energy sources as shown in Equation (3) to Equation (5).

$$B_{kWh} = P_{kWh} \cdot U_{SMP} \cdot P_{loss} \quad (3)$$

$$B_{REC} = \sum_{i=1}^{m} P_i \cdot k_i \cdot U_{REC,i} \quad (4)$$

$$B_{co_2} = \sum_{t=1}^{T} E_{co_2}(t) \cdot CER \quad (5)$$

Where, B_{kWh}: electrical pricing by improving the power curtailment(won), P_{kWh}: capacity of power transaction(kWh), U_{SMP}: power trading unit price(won/kWh), P_{loss}: power loss of line(%), B_{REC}: pirce of REC(won/kWh), P_i: power generation of i energy sources, k_i: weighting factor of REC in renewable energy sources, $U_{REC,i}$:price of REC(won/kWh), B_{CO_2}: cost of carbon emission(won) in target year, $E_{CO_2}(t)$: carbon emission in time interval(ton), T: time interval in target year, CER: unit cost of CER in time interval(won/ton)

3.2.2 Deferred investment benefit of power facility

The deferred investment benefit in power system infrastructure is as shown in Equation. (6) to Equation (9).

$$B_{\text{def}}(i) = \sum_{i=1}^{m} X_i \quad (6)$$

$$X_1 = C_{D/L} \cdot L_{D/L} \cdot N_{D/L} + C_{U/P} \cdot \frac{L_{D/L}}{P_{span}} \quad (7)$$

$$X_2 = C_{bank} \cdot k \quad (8)$$

$$X_3 = C_{T/L} \cdot L_{T/L} + C_{S/S} \cdot S_{type} \quad (9)$$

where, $B_{\text{def}}(i)$: deferred investment benefit in power system facility by scenario(won), i: scenario(i =1: small−scaled, i=2: medium−scaled, i =3: large−scaled), m: the number of scenario, $C_{D/L}$: construction cost of distribution feeder(won/km), $L_{D/L}$: the length of distribution feeder(km), $N_{D/L}$: the number of line in a distribution feeder, $C_{U/P}$: construction cost of utility pole(won/km), P_{span}: span of utility pole(m), C_{bank}: construction of main transformer(won/kW), k: the number of bank in substation(won), $C_{T/L}$: construction cost of transmission line(won/km), $L_{T/L}$: the length of transmission line(km), $C_{S/S}$: construction cost of substation(won/kW), S_{type}: type of substation

3.3 Present worth method

Economic feasibility is assessed by calculating the cost and benefit factors as values at the same point in time as shown in Equation (10).

$$PW = \sum_{1}^{n} \frac{CF}{(1+d)^n} \quad (10)$$

where, PW: prevent worth cost(won), CF: cash flow of i year(won), n: unit period of year, d: discount rate(%)

4. Case studies

4.1 Simulation conditions

In order to evaluate the economic feasibility of the VPL device to improve the hosting capacity of renewable energy sources, the simulation conditions shown in Table 1. are assumed in this paper. Table 2 also shows cost of the component of the VPL device, with a unit price of 90 [thousand won/kW] for the PCS and 500 [thousand won /kWh] for the battery. in addition the costs for operation and maintenance and the VPL platform are assumed 2.5[%] and 10[%] of the total cost of the VPL device. The replacement intervals for the PCS and the batteries of the ESS for the VPL device are set at 20 years and 10 year, respectively.

In addition, the installation cost for the power infrastructure components is assumed to be 4,520,000[thousand won/km] for underground T/L, 23,000,000[thousand won] for distribution S/S, 6,000,000[thousand won] for M.Tr, 98,000[thousand won/km] for D/L and 97,500[thousand won/km] for power poles. In addition, the introduction capacity of the VPL device is determined as 3[MW]/13[MWh] for the small scale model, based on the proposed optimal capacity estimation method, and the capacities of the medium and large scale models are assumed to be 30[MW]/120[MWh], 200[MW]/800[MWh] respectively with long term application of battery.

[Table 1] Economic evaluation conditions

items	contents
economic target year[year]	20
discount rate[%]	5.5
inflation rate[%]	3
price of SMP[won/kWh]	250.74
price of REC[won/kWh]	56.48

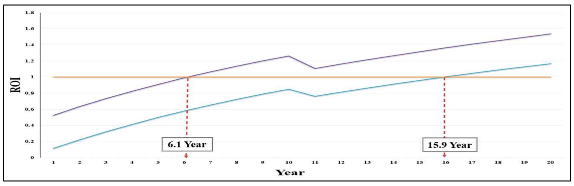
[Table 2] Costs of the VPL device

items		contents
ESS	PCS[thousand won/kW]	90
	battery[thousand won/kWh]	500
operating cost		2.5% of construction cost in ESS
cost of VPL platform		10% of construction cost in ESS

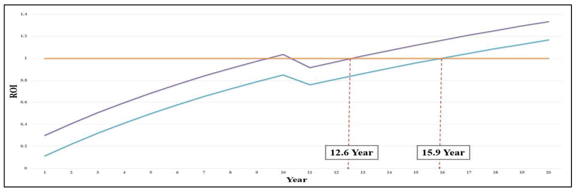
4.2 Economic evaluation to improve hosting capacity

Based on the above economic evaluation conditions, the economic evaluation of the VPL device to host renewable energy sources in D/L is shown as shown in Fig. 4. Where, Fig. 4(a) shows the return of investment (ROI) of the VPL device to accommodate small renewable energy sources, If only the benefits of improving the hosting capacity of renewable energy sources are considered, the ROI is about 15.9 years, while If the benefits of deferred investment in power grid infrastructure are additionally considered, the ROI is about 6.1 years, indicating that the economic feasibility can definitely be insured.

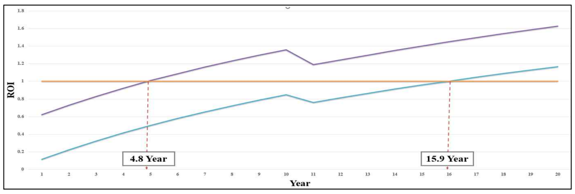
Fig. 4(b) is the ROI of the VPL device for hosting medium renewable energy sources, If only the benefits of improvement are considered. the ROI about 15.9 years, and If the benefits of deferred investment in power grid infrastructure is also considered. The ROI is about 12.6 years, indicating that the economic feasibility can definitely be ensured. And, Fig. 4(c) shows the ROI of the VPL device for large renewable energy sources, considering only the benefit of improving the hosting capacity of renewable energy sources, the ROI is about 15.9 years, while additionally considering the benefits of deferred investment in power grid infrastructure, the ROI is about 4.8 years, indicating that the economic feasibility can definitely be ensured.



(a) small-scale model



(b) medium-scale model



(c) large-scale model

[Fig. 4] ROI characteristics for introduction model in VPL device

5. Conclusions

This paper presented the Virtual Power Line (VPL) model as a feasible and economic solution to improve the renewable energy sources hosting capacity and proposed an analysis of the economic feasibility of the VPL device based on the on the scales of renewable energy sources using the net present value method. As a result of assessing the feasibility of the VPL device to connect renewable energy sources, the economic feasibility deteriorates as the cost of the VPL platform increases. It is found that selecting the optimal capacity of the VPL model is more effective than investing in existing energy facilities.

References

[1] Lu, X.; Alharbi, W.; Rosehart, W.D. "Distributed Battery Energy Storage Systems for Deferring Distribution Infrastructure Upgrades", Journal of Energy Storage, 2024.