J Electr Eng Technol Vol. 9, No. 5: 1501-1510, 2014
http://dx.doi.org/10.5370/JEET.2014.9.5.1501

ISSN(Print) 1975-0102
ISSN(Online) 2093-7423

A Techno-Economic Feasibility Analysis on LVDC Distribution System for Rural Electrification in South Korea

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Abstract – Low voltage direct current (LVDC) distribution system is a suitable techno-economic candidate which can create an innovative solution for distribution network development with respect to rural electrification. This research focuses on the use of LVDC distribution system to replace some of KEPCO's existing traditional medium voltage alternating current (MVAC) distribution network for rural electrification in South Korea. Considering the technical and economic risks and benefits involved in such project, a comparative techno-economic analysis on the LVDC and the MVAC distribution networks is conducted using economic assessment method such as the net present value (NPV) on a discounted cash flow (DCF) basis as well as the sensitivity analysis technique. Each would play a role in an economic performance indicator and a measure of uncertainty and risk involved in the project. In this work, a simulation model and a computational tool are concurrently developed and employed to aid the techno-economic analysis, evaluation, and estimation of the various systems efficiency and / or performance.

Keywords: DC distribution system, Techno-economic analysis, Annuity, Net present value, Sensitivity analysis, Power converters, Distribution system losses, Power outage cost

1. Introduction

The electricity distribution system was originally based on DC technology but thereafter, AC technology took over the power network due to its benefits as loss reduction with high-voltage transmission using transformers. However, a shift in technology and extensive research in power electronics during the last decades have brought about a renewed interest on DC technology in power system. The Korean Electric Power Corporation, hence-forth referred to as KEPCO plans to develop its current medium-voltage (MV) network for rural electrification using the low-voltage DC (LVDC) technology.

With increases in research and development in the automation of distribution system, KEPCO was able to solve some of the challenges in the electricity distribution business. Recent studies clearly validated the use of the DC distribution system in residential buildings in South Korea [1]. Other reference literature such as [2-5] demonstrated the economic potential and viability of the LVDC distribution system in Finland and also, enumerated their benefits and incentives acquired while using this form of electricity distribution. In [2], a set of methodology and formulation for evaluating LVDC economic benefits was addressed when compared to the conventional LVAC distribution system. In [2-4], the authors showed how to improve the reliability and quality of service to customers by using the LVDC distribution system.

In an effort to improve the efficiency and reliability of distribution system by reducing losses and power outages alike, studies on the replacement of traditional medium voltage AC distribution system with the low voltage DC distribution system are heavily researched on in industries and academia [3].

This paper presents a more precise and clinical approach on the techno-economic evaluation, assessment and strategic decision-making for KEPCO's proposed LVDC system compared to the conventional MVAC system. The losses in the proposed system and the power outage were quantified not only by using simulation tools but also, aided with systems reliability mathematical formulations, computation and statistics. The economic analysis method is based on both the net present value (NPV) and sensitivity analysis with respect to key parameters. It was carried out to observe the viability of the LVDC project in South Korea. The results in this study would give an affirmative indication on the viability of the LVDC system in South Korea. Hence the findings in this paper can be a standard guideline for the implementation of KEPCO's future LVDC systems.

2. KEPCO's Electricity Distribution Network

The target area of the project study forms an integral section of KEPCO's overall distribution network system in

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Received: November 4, 2013; Accepted: April 30, 2014

South Korea. It is located on a mountainous region close to Boeun in Chungbuk province. The network consists of six power transformers with a 22.9 kV conventional medium-voltage AC (MVAC) network with a total distance of 3.569 kilometers of which 79.4% of the network is connected using underground cable and 20.6% using the overhead cable as shown in Fig. 1. The network is a three-phase four-wire system earthed every 200 meters on the network. It has an average load capacity of 65 kW that accommodates over 20 residential customers with an average load of 3kW.

The proposed active LVDC system will provide a safe and reliable electric power transmission from the medium voltage network to the low voltage customers via a power transformer and the DC link as shown in Fig. 2, which connects the rectifier at the grid end and six power converters at the customers end.

In this research, we will adopt the bipolar DC distribution system with a DC distribution topology having a rated voltage level of ±750 V_{DC} [2, 3], as shown in Fig. 2. The reason for adopting the bipolar system with a DC distribution network topology is to take advantage of the better connectivity and high reliability of electricity supply associated with the design. In addition, the ± 750 V_{DC} is selected because the low-voltage level is defined between 75 and 1500 V_{DC} according the European standard (EU LVD 72/23/EEC) [2].

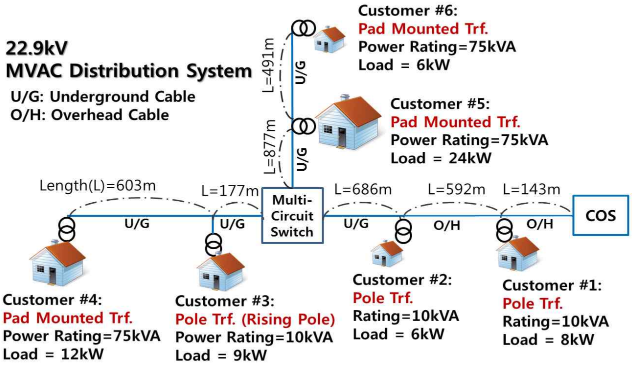

Fig. 1. Single-line diagram of the KEPCO's traditional MVAC distribution network at Boeun

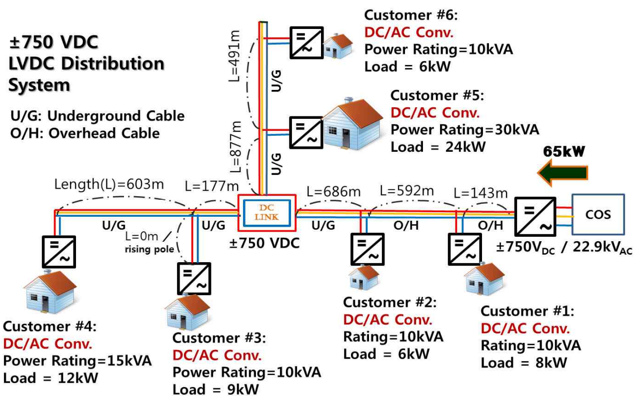

Fig. 2. Configuration of the proposed LVDC distribution system to replace the traditional MVAC at Boeun

In the bipolar LVDC system, the main distribution lines of system consist of three conductors, which are connected respectively to the positive pole terminal, the negative pole terminal and the grounding-neutral terminal of the AC/DC power converter. Load inverters can be connected between three conductors with multiple options and variation.

Compared to the MVAC system, the installation and maintenance of power facilities such as distribution cable, electric pole, and protection devices are less cumbersome to conduct in the LVDC system. Also, the LVDC system can improve voltage quality resulting from the converter's voltage control scheme. For this same reason, network disturbances such as voltage fluctuations and dips can be compensated and eliminated in the customer operating voltage [3]. In addition, because the LVDC distribution system can create its own protection zone [2], the risk of total system collapse or brown/blackout is uncommon. This benefit certainly indicates the level of power electronics penetration on the distribution line resulting in an improved reliability, quality, and total system stability.

Obviously, the LVDC distribution system has its own challenges when compared to the MVAC system. Firstly, the ±750V LVDC distribution system has a lower transmission capability than the 22.9kV MVAC distribution system. Secondly, the losses in the distribution line increase in the LVDC system when compared to the MVAC system. Finally, the power electronic devices introduced into the system, invokes new challenges in the LVDC system such as shorter lifespan of the power electronic converters compared to the life span of conventional AC transformers.

Table 1. Systems parameters for MATLAB simulations and techno-economic analysis

Parameters	Values
Distribution Systems Economic Life-Time [yr.]	40
Real Interest Rate [%/yr.]	7.0
Corporate Tax Rate [%/yr.]	22.0*
Price of Electricity[KRW/kWh] (KEPCO 2013)	93.30
Average Power Factor	0.93
Efficiency of Power Electronics Devices[%]	97.0
Transformers Economic Life-Time [yr.]	40
Power Electronics Economic Life-Time 1st Generation [yr.]	10
Power Electronics Life-Time 2nd and 3rd Generations [yr.]	15
Average Fault Interruption Time [h]	1
Peak Operating Time of Losses[h]	1000
Average Power of the Feeder [kW]	65
Average Peak Load per Customer[kW]	3
Annual Customers Load Growth [%/yr.]	0
Number of Low Voltage Customers End	6
Number of Customers Load	21
Fault Frequency of Power Converters [fault/100units, yr.]	0.3*
Fault Frequency of Power Transformers [fault/100units, yr.]	0.5
Fault Repair Time of Power Converters [h]	1 ~2*
Fault Repair Time of Power Transformers[h]	4 ~ 6*
Average Number of Outages on MV line in S. Korea [/yr.]	1284

*varies during systems analysis

3. Systems Simulation

The system specifications for the MVAC and the LVDC and economic assessment parameters are listed in Table 1. The systems component modeling is vital for the simulation and analysis of the distribution system to analyze the systems component loss mechanism under its operating conditions. Both systems have been modeled in MATLAB/ Simulink. The modeling of the power electronic converter of the LVDC system was realized using power electronic device models such as IGBT and diode models.

3.1 MVAC system specification and modeling

The traditional three-phase four-wire MVAC distribution system in Korea is primarily centered on the principles of operation based on its nominal line-to-line voltage level between 22.9kV and 0.38 kV as shown in Fig. 3. According to KEPCO's installation guide, distribution lines are grounded every two hundred meters.

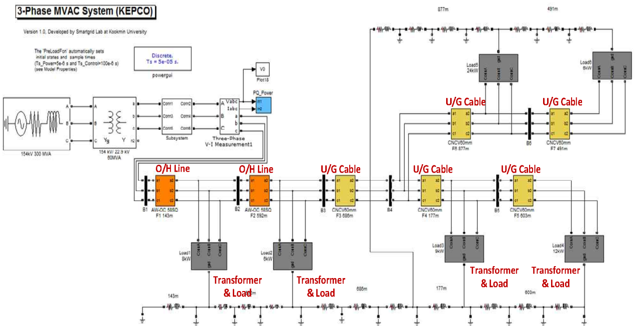

Fig. 3. Overall MVAC distribution system modeled in MATLAB/Simulink

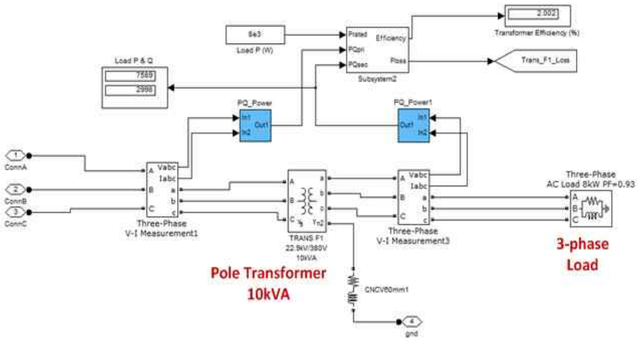

Fig. 4. AC transformer and load models in MATLAB / Simulink

Table 2. System parameters for MVAC distribution systems

Category	Parameter
O/H Line	ACSR/AW-OC 58SQ R=0.4842 [Ohm/km], X=0.4388 [Ohm/km]
U/G Cable	CNCV 60SQ R=0.3874 [Ohm/km], X= 0.1632 [Ohm/km]
Transformer	10kW Pole transformer: %Z = 2.8 ± 10%
	75kW Pad-mounted transformer: %Z = 4.0 ± 10%, Efficiency = 97.9% at the rated load

In order to describe the distribution system, the AC systems transformers were modeled as shown in Fig. 4 using MATLAB based on the loading parameters of the network and during the simulation. Table 2 lists the system parameters of the overhead (O/H) distribution lines, underground (U/G) distribution lines and transformers of the MVAC system.

3.2 LVDC system specification and modeling

In order to describe the LVDC system as shown in Figs. 5 and 6, we adopted the three-level Neutral-Point-Clamped (NPC) Voltage Source Converter (VSC) configuration for the LVDC distribution system. The VSC design for bipolar ±750V_{DC} set-up satisfies the Korean and international standards for low voltage DC distribution. Using the bipolar structure is more reliable compared to the mono-polar structure. The system parameters for simulation of the LVDC system are listed in Table 3.

Because the line current in the ±750 V LVDC system are larger than that of the conventional 22.9 kV MVAC

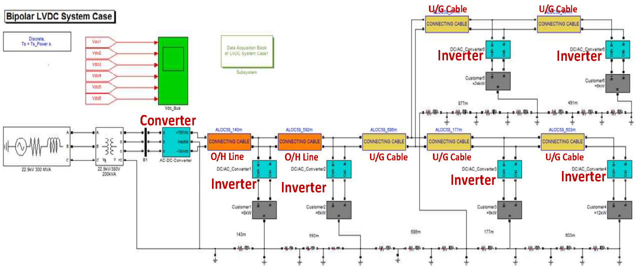

Fig. 5. Overall LVDC distribution system modeled in MATLAB/Simulink

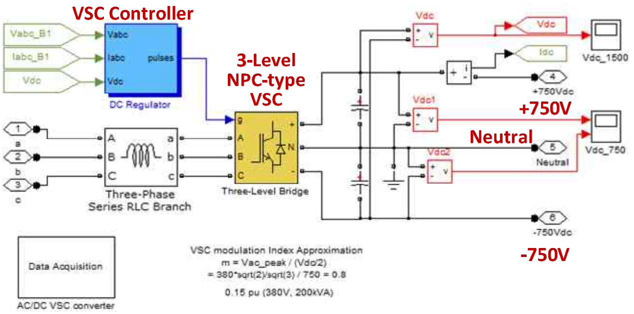

Fig. 6. Three-level power converter in MATLAB/Simulink

Table 3. System parameters for the LVDC distribution lines and components

Category	Parameter
O/H Line	ACSR/AW-OC 58SQ R=0.4842 [Ohm/km], X=0.4388 [Ohm/km]
U/G Cable	CV 250SQ R=0.0972 [Ohm/km], X=0.1170 [Ohm/km]
Converter	Three-level NPC-type voltage source converter (Output voltage: +750, 0, -750 V_{DC})
Inverter	Efficiency = 97% at the rated power

distribution system, voltage drop and energy loss will both be an important issues in the LVDC system distribution network design. To reduce losses and voltage drop, thicker distribution wires with less resistance are needed. For this reason, an alternative underground cable CV 250 SQ is tested in the LVDC system in lieu of the CNCV 60SQ underground cable in the MVAC system as listed in Table 3. On the other hand, it is difficult to use thicker cables for the overhead lines because the capability of electric poles to support heavy and thick overhead cables is limited. Therefore, the same overhead cables as ACSRAW / OC 58SQ are tested.

3.3 Systems losses comparison and discussion

The results obtained from simulation are summarized and presented in Tables 4. Here, the efficiency of the power converters is 97% and the power factor is 0.93. The losses on the MVAC system is quite small 1.93% compared to that of the LVDC system 7.73%.

Table 4. Systems' loses simulation results when converters efficiency is 3% of the power converters losses

Losses	MVAC	LVDC
Line and cable loss [W]	5.0	1612.4
Transformers/ Converters loss [W]	(Transformer) 1,272.0	(DC/AC) 1950.0
		(AC/DC) 2086.8
Total loss [W]	1,277.0	5649.2
Input power at the COS [W]	66,277	73,119
Total loss [%]	1.93%	7.73%

4. Lifetime Economic Comparative Analysis

The economic analyses are conducted using optimization process. The investment costs and operational costs of both systems were accounted for on a long-term basis based on discounted cash flow (DCF) method. To execute economic comparative analysis on life cycle cost (LCC) of the systems in question, we assume each of the system to be a newly built system; which means that we are not looking at the cost of renovating or replacing the present traditional MVAC distribution network with the LVDC system. In other words, our concern here is on the economic cost comparison, assessment, and evaluation of implementing a brand new MVAC and LVDC distribution system under a given technical and economic specifications.

4.1 Annual cost of the economic components

All the individual constituent costs can be grouped into three main components as:

$$C_{Total} = C_{Con} + C_{Qos} + C_{Oper} \tag{1}$$

where the individual components can be defined as

- ✓ ***Construction cost*** [C_{Con}]: This is the capital or investment cost (C_{invest}) and it consists mainly of the facility, equipment, installation, and overhead cost.
- ✓ ***Quality of service / supply* (*QoS*) cost** [C_{QoS}]: This includes the power outage cost (C_{poc}) and standard compensations to customers.
- ✓ ***Operation cost*** [C_{Oper}]: This includes cost of the systems losses ($C_{Loss\_\{system\}}$) and also, the cost for the systems maintenance and fault repair ($C_{M\&R}$).

It is important to note that the calculation parameters are considered as their average or expected values. The unit costs of the distribution network components as summarized, reviewed, and published by KEPCO (November 2012) are utilized in our calculations for estimating the four constituent costs which are investment costs, cost of losses, cost of power outages and the M&R costs. All the constituent costs are treated separately for the MVAC and LVDC systems.

4.1.1 Systems investment costs

The costs of the systems initial investment, i.e., during the start of the project, can be estimated as

$$C_{invest} = (UP_{comp} + C_{intall}) \times QL_{comp} \tag{2}$$

where C_{invest} is the investment cost, UP_{comp} is the unit price of the components, C_{intall} is the installation cost, and QL_{comp} is the quantity or length of the network components.

The C_{invest} is then expressed as a function of the annual investment cost and the annuity factor using the annuity method. The annual investment cost (C_{a_invest}) is given as

$$C_{a\_invest} = C_{invest} \times \varphi \tag{3}$$

with φ, the annuity factor mathematically expressed as

$$\varphi = \frac{r/100}{1-\left(1+r/100\right)^{-t}} \tag{4}$$

where r is the discount rate in %; t is observation period of the investment in t years. The detailed derivation procedure of the annuity factor is provided in Appendix of this paper.

The amortization period in this study is 40 years for the transformers, 10 years for the 1st generation power electronics converters, and 15 years for the 2nd and 3rd generation power electronics converters. This means that the power electronic converters for the LVDC distribution network will be replaced twice during the economic life time (i.e., 40 years) of the LVDC system.

4.1.2 Systems power outage/Interruption costs

The power outage cost is predominantly influenced by the reliability and the duration of repair/replacement of the faulty network components and also by the auto-reclosing protective operation [5]. The cost of power outage is summarized as:

$$C_{poc} = C_{nde} + C_{arc} \tag{5}$$

where,

C_{poc} is the annual cost of power outage,
C_{nde} is the annual cost from the non-delivered energy,
C_{arc} is the annual cost of power interruption caused by automatic reclosing operation.

This paper is aimed at estimating the annual unplanned power outage cost for residential customers using the estimated C_{nde} and C_{arc} values. The annual cost resulting from non-delivered energy C_{nde} is estimated in (6) using the failure/fault rate of the network components and the interruption parameters constants a_j and b_j as

$$C_{nde} = a_j \times (\textit{load interrupted}) + b_j \times (\textit{expected energy not supplied}) \tag{6}$$

where a_j is the power outage cost parameter for the power not supplied to the load section or customer group j [KRW/kW] and b_j is the time dependent power outage per unit cost constant parameter for the energy not supplied to the load section or customer group j [KRW/kWh]. The interruption parameters, a_j and b_j, are obtained based on the residential (domestic) customers interruption data statistics in Korea as shown in Table 5. The interruption parameters are derived using the interruptions duration and the annual peak demand normalized by using the load factor of the customer mix in the distribution network [6]. The outage cost can be calculated when the unit costs of each power quality factors are defined. Reference [5], shows the specified and corrected values of unit cost parameters for outage cost estimation in Finland. In South Korea, the price of unplanned (unexpected) interruption for residential customer load is estimated as (a_j=14.81 KRW/kW, b_j=148.1 KRW/kWh) according to information from KEPCO in 2010 as listed in Table 5. Furthermore, detailed definition and analysis of these unit costs in Finland were presented in [7].

Table 5. Customer's Interruption Cost in South Korea

Intr. Time / Load type	1 min	20 min	1 hour	2 hour	4 hour	8 hour
Industry	2.99	4.36	9.20	24.88	117.02	440.20
Offices	2.03	2.91	5.96	15.51	69.13	256.99
Agriculture	0.10	0.19	0.72	4.38	78.75	1394.59
Service	2.53	3.80	8.50	24.95	134.10	583.82
Residence	0.0017	0.00274	0.01481	0.14154	4.85021	112.722

(Source KEPCO, 2010) [Unit: 1,000Won/kW]

The average failure rate of the power electronics converters is 0.3 faults per year/100 units and that for the pole mounted transformers is 0.5 faults per year/100units, with fault repair time (t_{rep}), respectively [8, 9]. If we are to base our calculations on the failure rate of the network components, a more precise assumption will be to compute the power outage cost based on the incipient fault (auto-reclosing) and the failure rate of the key network components such as the transformers and power converters. The power outage cost due to other network components such as switches and cables are therefore omitted from this research. With these preceding assumptions, the practical annual power outage costs (POC) for the distribution network systems in a given zone can be expressed mathematically as

$$C_{nde} = \sum_{j \in J} \lambda_j \times \left(a_j + b_j \times t_{rep}\right) \times P_j \times n_j \tag{7}$$

where, n_j is the number of load sections j; λ_j is the sum of the individual distribution network component failure or fault per year in section j; t_{rep} is the fault repair time for the network component; and P_j is the average yearly power for load section j.

For the fast and the delayed auto-reclosing interruptions, the annual cost of auto-reclosing will be computed by

$$C_{arc} = \sum_{k \in K} \left\{ \left(\omega_{kfar} \times a_{ifar} + \omega_{kdar} \times a_{idar} \right) \times P_k \times n_k \right\} \tag{8}$$

where n is the number of load sections k; ω_{kfar} is the sum of the fast auto-reclosing fault frequency per year in section k; ω_{kdar} is the sum of the delayed auto-reclosing fault frequency per year in section k; a_{kfar} is the cost parameter of a fast auto-reclosing unit for power not supplied to load section in zone k [KRW/kW]; a_{kdar} is the cost parameter of a time-dependent delayed auto-reclosing unit for energy not supplied to load section in zone k [KRW/kW]; and P_k is the average yearly power for load section in zone k. However, for the fast auto-reclosing related to the outages in Eq. (8) is assumed to be zero when estimating the total power outage cost for the LVDC distribution system. This is due to the fact that the converters in the LVDC link can still supply power to residential customers during the short time duration of interruptions prior to the system's restoration to normal.

4.1.3 Cost of systems losses

The systems losses due to primary transformers, converters, lines, and distribution transformers were all estimated using MATLAB / Simulink simulation.

The simulation results obtained for the system's losses are summarized and classified in Table 4 and are further evaluated based on the definition of the peak operating time of losses as defined above. The cable losses obtained from the systems simulation can be estimated as

$$PL_{ACcable} = 3 \cdot \sum I_i^2 \times R_i \times L_i \tag{9}$$

$$PL_{DCcable} = 2 \cdot \sum I_i^2 \times R_i \times L_i \tag{10}$$

where $PL_{ACcable}$ is the cable loss of MVAC distribution network; $PL_{DCcable}$ is the cable loss of LVDC distribution network; R_i is the resistance per unit length of the line section i; L_i is the total length of line section i; and I_i is the line current in line section i. For the MVAC system, coefficient '3' is multiplying the power loss due to the fact we are estimating the losses on a 3-phase AC line (current flow via the three lines) and for the LVDC system, coefficient '2' is multiplying the power loss on the DC line which consist of the positive and negative polarity (current flow via the ± polarities).

Eqs. (9) and (10) can give an instantaneous line losses at a specific time. To obtain the average annual loss of the distribution network, we applied the average load currents to (9) and (10). However, to consider the time varying characteristics of load patterns more in detail, the concept of load factor and/or loss factor can help to obtain more precise estimate of distribution line losses. The load factor is defined as the ratio of the average load in kilowatts supplied during a designated period to the peak or maximum load in kilowatts occurring in that period and the loss factor is the ratio of the average power loss divided by the losses at the time of peak load in [10]. Reference [11] presents two ways to calculate the indices practically.

The total power losses of the MVAC (P_{Tmvac}) and LVDC (P_{Tlvdc}) distribution networks can be obtained as

$$P_{Tmvac} = PL_{pt} + PL_{dt} + PL_{ACcable} \tag{11}$$

$$P_{Tlvdc} = PL_{pt} + PL_{rec} + PL_{inv} + PL_{DCcable} \tag{12}$$

where PL_{pt} is the primary transformer losses; PL_{dt} is the distribution transformers losses; PL_{rec} is the AC/DC rectifier losses; and PL_{inv} is the customer-side inverter total losses.

The total energy losses of the MVAC and LVDC distribution networks from (11) and (12) then become

$$E_{Tmvac} = PL_{ACcable} \cdot tp_{loss} + 8760 \cdot (PL_{pt} + PL_{dt}) \tag{13}$$

$$E_{Tlvdc} = PL_{DCcable} \cdot tp_{loss} + 8760 \cdot (PL_{pt} + PL_{rec} + PL_{inv}) \tag{14}$$

where tp_{loss} denotes the peak operating time of losses, i.e., 1,000 hours.

Therefore, the total cost of losses annually for the MVAC and LVDC distribution networks is estimated as follow:

$$C_{Loss\_mvac} = CP_{mar} \times P_{Tmvac} + CE_{ave} \times E_{Tmvac} \tag{15}$$

$$C_{Loss\_lvdc} = CP_{mar} \times P_{Tlvdc} + CE_{ave} \times E_{Tlvdc} \tag{16}$$

where CE_{ave} is the average market price of energy (energy charge) in South Korea that is *93.3 KRW/kWh* and CP_{mar} is the marginal price of power (demand charge) for different voltage levels estimated as $CP_{mar} = 93{,}300 KRW/kW, yr.$ We took the marginal cost into consideration in our calculation due to the fact that when dealing with losses at the low voltage systems, the cost per kW of loss incurred is usually huge [12].

4.1.4 Systems Maintenance and Repair (M&R) costs

The systems maintenance and repair costs consist of three components as follows.

Cost of Maintenance *(Planned)* is the preventive maintenance cost such as periodic and predictive check and evaluation of the network components. The total planned maintenance cost is the cost of service (consumables and personnel) before the occurrence of the fault or outage in the distribution network.

Cost of Maintenance *(Unplanned)* is the repair maintenance cost of the network components. Because this cost is incurred after the occurrence of fault or the component breakdown, we thus included it as part of the fault repair cost in our analysis.

Cost of Fault Repair is based on the failure rate of the network component, i.e. the average cost of component service per piece or per kilometer times the total number of component or distance on the distribution network. It is expressed mathematically as

$$C_R = (URP_{comp}) \times QL_{comp} \times \lambda_{comp} \tag{17}$$

where C_R is the fault repair cost, URP_{comp} is the unit repair price of the components, λ_{comp} is the failure frequency/rate of components, and QL_{comp} is the quantity/length of the network components respectively.

Fault repair cost should not be mistaken with interruption cost. Actually, fault repair cost is the cost of working materials, personnel labor and spare parts incurred for the repair of a faulty or broken network component. It is highly dependent on the type of component and extent of the fault or damage.

4.1.5 Annual economic constituent costs assessment and evaluation - results and discussion

The results obtained from the analysis of all the economic costs on an annual basis are penciled in Table 6. The huge incremental running (operational) cost of 4,226,299 KRW for the LVDC system as a result of the system losses, can be compensated from the cost savings of about 23,425 KRW in power outage cost and 705,063 KRW from the cost of M&R savings when compared to that of the MVAC network.

Table 6. Comparison of the annual economic constituent monetary equivalent costs for LVDC and MVAC distribution systems

Economic Factor	MVAC (KRW)	LVDC (KRW)	Difference (KRW)
Construction Cost	541,271,037	500,532,102	40,738,935
Losses Cost	1,043,711	5,270,010	-4,226,299
M&R Cost**	884,403	179,340	705,063
Power Outage Cost	29,405	5,980	23,425
Total Cost	543,228,556	505,987,432	37,241,124

**Excluding material costs

While the increase in investment cost for the LVDC system is as a result of the harsh price in power converter, there are significant savings in low-voltage components such as cost of cables, insulating materials, electric poles as well as lower installation costs of network components when compared to medium voltage system. It can be noticed from the total economic costing, that the LVDC system yields a cost savings of roughly 37,241,124 KRW which is about 6.9% the total cost of the MVAC system.

4.2 Life Cycle Cost (LCC) and Performance Measure Analysis (NPV) for MVAC and LVDC systems

Here, an efficient tool was developed in Microsoft Excel on the basis of cash flows. While observing the discount rate, the economic cost difference and NPVs were evaluated. In Fig. 7, the economic lifetime costs estimation for the replica MVAC system and the proposed LVDC system are tabulated when a discount rate of 7 % is observed during the 40 years economic lifetime. The figure below shows the distribution and variation of cash flow for the total life cycle cost of the LVDC system based on earnings before interest, taxes, depreciation and amortization (EBITDA), annuity and DCF as a function of the discount rate and system lifetime. The figures show how the cost of the systems components depreciates overtime (A) while the operational cost increases (B). Also with high discount rate, it can be noticed from the figures that both the LCC of the investment (A) and operation (B) decreases.

4.2.1 The Discounted Cash Flow (DCF) / Net Present Value (NPV) theory and analysis

The Net Present Value (NPV) and Internal Rate of Return (IRR) are key economic indicators which are often used as economic tools to evaluate the economy of projects. In this research, we will focus on the use of the NPV method. NPV is our preferred choice since IRR can incorrectly rank mutually exclusive projects in many cases. Other drawbacks such as its inability to indicate the size of the project investment, providing more than one IRR values for projects with irregular cash flows, and furthermore, as an objective financial indicator, its inability to consider subjective non-financial factors make IRR less favorable for our analysis [13]. To determine the present worth, it involves a process known as discounting hence the term discounted cash flow (DCF) technique. Thus, the discounted annual cost can be expressed as

$$NPV = I_0 + 1/\varphi \times \{AC \times (1 - TR) - Depr \times TR\} \qquad (18)$$

where, I_0 is the investment cost; φ is annuity factor; AC is the annual costs; TR is the taxation rates; and $Depr$ is the depreciation obtained via linear estimation method [14].

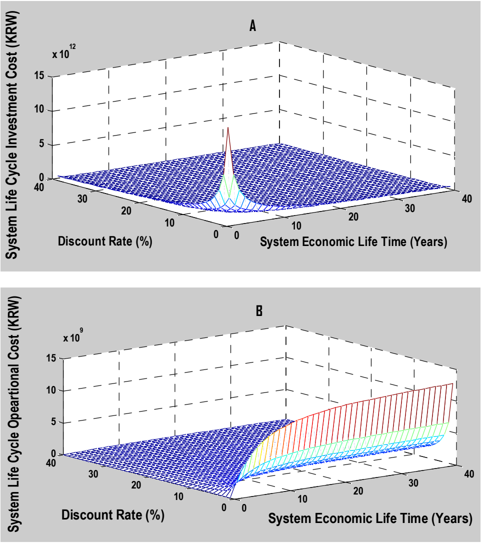

Fig. 7. Surface plot of the LVDC system life cycle cost LCC on investment and operations based on (EBITDA, Annuity, and DCF) as a function of discount rate (%) and system life time (years).

4.2.2 NPV's evaluation results and discussion

The results in Table 7 give a clear indication of the economic performance measures derived from (18). The decision rule here is to accept projects with positive NPVs and the results of the NPVs evaluation in both systems as presented in Table 7 showed positive NPV outcomes for both the LVDC and MVAC distribution systems. The NPV outcome of the LVDC distribution system is relatively lower than that of the MVAC system, implying that the LVDC project has a higher degree of viability compared to that of the MVAC project.

Table 7. Lifetime cost analysis using NPVs

Economic Factor	MVAC Cost (KRW)	LVDC Cost (KRW)
Investment Cost	541,271,037	500,532,102
Operations Cost	-19,332,647	20,027,301
Overall NPVs	521,938,390	520,559,402

4.3 Strategic economic decision-making approach for the LVDC system

The performed economic analysis forecasts the cost of the proposed system and the economic indicators used in our evaluations on the viability of the project. Nevertheless, these economic indicators are highly sensitive to what calls for concern on the "what if…" questions by the projects' decision makers to handle the problem of uncertainty and risk. At a conceptual level, Flanagan et al. defined it as a deterministic modeling technique which primarily answers the "what if…" questions [15]. Excluding the inherent uncertainty in failures, the approach applied in this research is based on an engineering economics mathematical technique for quantifying risk and handling project uncertainty, i.e., the sensitivity analysis.

4.3.1 Sensitivity analysis of economic parameters and indicator for the ±750V bipolar LVDC system

It is conducted to investigate the risk and uncertainties involved in implementing the LVDC system. KEPCO can proceed to reduce risk and uncertainty in the project implementation and define apt risk mitigation strategies. The approach in this research is the linear sensitivity analysis on a univariate basis [15]. Here a technique from the linear control theory in systems engineering called quasi-linearization is used to obtain our results.

The performance measures of the project viability (NPVs) are recalculated for every change on the key variables and to perform this task, the sensitivity analysis variation ladder was built with the aid of the estimated values from the sensitivity indicators (SI) which is mathematically expressed as

$$SI = \frac{\left(NPV_{bc} - NPV_{st}\right)/\left(NPV_{bc}\right)}{\left(X_{bc} - X_{st}\right)/\left(X_{bc}\right)} \tag{19}$$

where, X_{bc} and NPV_{bc} are the values of the variables and NPV in the base case. X_{st} and NPV_{st} are the values of the variables and NPV in the sensitivity test respectively. The obtained result of SI compares percentage changes in NPVs with percentage change in a variable or combination of variables [15].

4.3.2 Sensitivity test results and discussion

Illustrated in Fig. 8 is the sensitivity of the NPVs with respect to changes in the assumptions relating to variables used during its computation in (19). On varying the cost of power electronics converters, the average market price of electricity, the cost of operations, the cost of construction and the discount rate on a percentage basis of ± 1%, ± 5%, ± 10%, ±25%, ±50%, ±75% etc., the NPVs of the LVDC system were noticed to vary respectively.

From the spider diagram in Fig. 8, the flatter the curve/ line the more sensitive NPV will be to variation in that parameter. Accordingly, it can be seen from Fig. 8 that variations in the estimates for the electricity price and the cost of power electronics will have a greater impact on the NPVs than identical variations in all the other parameters. Since the cost of power electronics has been identified in our project's techno-economic analysis as having some risks associated with its estimates, it can be observed that slight percentage changes in the cost of power electronics lead to drastic percentage changes in the NPVs, i.e., it is the most risky parameter that is more sensitive to changes due to the influence of the huge cost of power electronics in investment cost, which can also be observed in the spider diagram. On the other hand, the electricity price has a dominant effect on the operational cost (incurred from losses) in the LVDC system. Therefore, caution should be exercised by KEPCO on these two parameters during and/or after the project implementation stage.

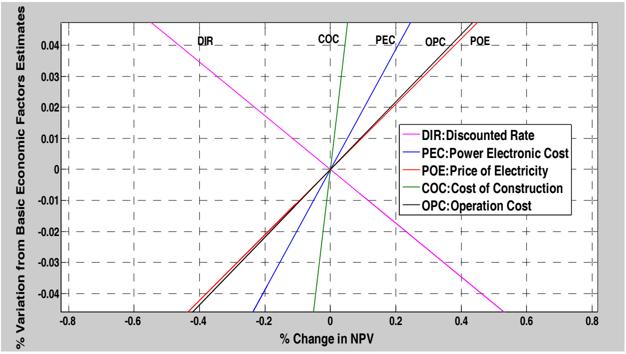

Fig. 8. Spider diagram of the proposed LVDC distribution system

5. Conclusion

As KEPCO plans to replace some of its existing rural MVAC distribution system with the LVDC system, concerns in terms of the financial consequences and economic viabilities of investing in such a huge project pose a challenge on KEPCO. We have shown in the foregoing section that the LVDC distribution system is the more cost-efficient option with a cost savings of more than 5% of the total cost for the MVAC system. However, from the sensitivity analysis, the huge losses from the LVDC and the high cost of power electronics are critical setbacks which result in extra cost burdens on the system operations and investment costs as a result of the dual replacement of the power converters during the lifetime of the LVDC system. In addition, the losses of the LVDC system is a major con on the LCC of the system and can be fully compensated or traded for via its pros on power outage cost and M&R cost savings. Besides, as increases in research and development in power electronics continue to grow and costs continue to decrease as their lifespan increases, there are possibilities that this will ultimately make more efficient power converters available to consumers at a cheaper price in no distant time. Thus, the estimated total LCCs of implementing the LVDC system is economically viable when compared to the traditional MVAC distribution network at typical transmission power based on the evaluated financial indices (NPVs) of both systems. To conclude, the LVDC system is thus a suitable alternative candidate and a more efficient replacement of the MVAC distribution network for rural electrification.

Appendix

A.1 Equations for annuity factor

The present value of the general cash flow in a project i.e. the sum of money (Cinvest) invested at an interest or

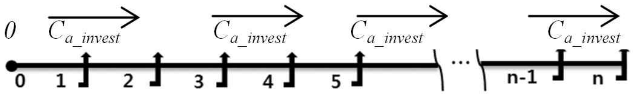

Fig. A.1 A set of cash flow of invest cost

discount rate of r [%] per annum that will produce (Ca_invest) at the end of n years (t) is in accordance with the formulae as

$$C_{invest} = \sum_{t=0}^{n} \frac{C_{a\_invest(t)}}{\left(1+d\right)^{t}} \tag{A1}$$

where d= r/100 and the term 1/(1+*d*)*t* is the present worth factor used to obtain the present day value C_{invest} of a sum of money $C_{a\_invest(t)}$ available at year(t) in the future at an annual rate of *r* %.

Define a discount factor as $a = 1/(1+d)$ for simplicity and substitute it in (A1). Then,

$$C_{invest} = aC_{a\_invest} + a^{2}C_{a\_invest} + a^{3}C_{a\_invest} + \dots a^{n}C_{a\_invest} \tag{A2}$$

$$aC_{invest} = a^{2}C_{a\_invest} + a^{3}C_{a\_invest} + \dots a^{n}C_{a\_invest} + a^{n+1}C_{a\_invest} \tag{A3}$$

Subtracting (A2) from (A3) yields

$$C_{invest} = \frac{aC_{a\_invest} - a^{n+1}C_{a\_invest}}{1-a} = \frac{aC_{a\_invest}\left(1-a^{n}\right)}{1-a} \tag{A4}$$

Then, multiplying the numerator and denominator by (*1+d*) gives

$$C_{invest} = C_{a\_invest}\left[\frac{1-\left(1+d\right)^{-n}}{d}\right] \tag{A5}$$

With *t=n,*

$$C_{a\_invest} = \frac{d \times C_{invest}}{1-\left(1+d\right)^{-n}} = \frac{\left(r/100\right) \times C_{invest}}{1-\frac{1}{\left(1+\left(r/100\right)\right)^{t}}} \tag{A6}$$

Therefore, the annuity factor in (4) can be obtained as

$$\varphi = \frac{r/100}{1-\left(1+r/100\right)^{-t}} \tag{A7}$$

Acknowledgements

This research was supported by the KEPCO (Korea Electric Power Corporation) under the project entitled by “AC/DC hybrid distribution network design and analysis.”

This research was also supported by the Ministry of Science, ICT and Future Planning (MSIP), Korea, under the ITRC support program (NIPA-2014-H0301-14-1005) supervised by the NIPA and the National Research Foundation of Korea (NRF) grant funded by the MSIP (No. 2010-0028509).

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