Feasibility Study of Integrated Power System with Battery Energy Storage System for Naval Ships

So-Yeon Kim[1], Byung-Geuk Cho[1], Seung-Ki Sul[1]
[1]Electrical Engineering & Computer Science, Seoul National University, Republic of Korea
E-mail: sykim5310@eepel.snu.ac.kr

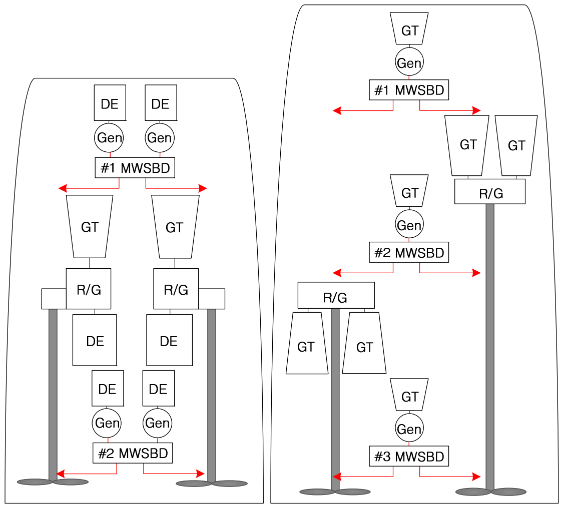
***Abstract*- Korean navy is now investigating how new naval destroyer can be designed by Integrated Full Electric Propulsion (IFEP) system. The operating cost of the electric propulsion system is smaller than that of the mechanical propulsion system. However, the existing IFEP system is still spending an enormous fuel due to Navy's conservative operating concept-Dual Generator Operation-for higher reliability. To improve the fuel-efficiency of the IFEP power system, the Single Generator Operation (SGO) is a rational solution because it could maximize the load factor of the generator. But the SGO is difficult to be accepted by the Navy as a reliable operating concept without full back-up of the entire electric power including propulsion power. This paper proposes a novel IFEP system having Battery Energy Storage System (BESS) which can guarantee reliable SGO. The feasibility, effectiveness and some design requirements of the proposed Integrated Power System (IPS) is discussed by computer simulations and reference data.**

I. Introduction

As a plan is currently set up for new Korean new naval destroyer class (KDDX), navy is now seeking a novel power system structure to reduce the life-cycle cost of the ship. KDDX will be lighter than the previous KDX-III class (10,000 ton of full load displacement), but install state-of-art weaponry of high power rating such as AEGIS system. Integrated Power System (IPS) is more suitable for the requirement of high power-density than the conventional mechanical propulsion systems such as CODOG (Combined Diesel Or Gas-turbine) or COGAG (Combined Gas-turbine And Gas-turbine) as shown in Fig. 1.

CODOG system has been mainly adapted to the high speed naval combatant of which displacement is less than 5000 tons. Normally, diesel-engines serve for cruising operation whereas gas-turbines serve for maximum speed. In case of large combatant over 5000 tons, the diesel-engine is too heavy to manage the required cruising power. And, COGAG system is a natural choice due to the high power-density of gas-turbine. Although single gas-turbine of each propulsion shaft can serve maximum speed operation, two sets of machines are established for higher redundancy, satisfying, so called, N+1 redundancy policy. The shipboard generation system is also established with N+1 redundancy against generator-trip.

This conventional power system is unable to draw the affordable propulsion power as common power sources without help of such as shaft-generator. Therefore, IPS is a solution for better fuel-efficiency of KDDX. IPS can manage the total installed power efficiently on the integrated architecture of ship service loads and propulsion loads.



(a) CODOG and 4 Diesel gensets (b) COGAG and 3 Gas-turbine gensets
Fig. 1. Mechanical propulsion system of conventional Korean destroyer.

Although there are lots of research for improvement of IPS performance, the proven example of IPS applied on destroyer class is just Type-45 class of Royal navy and DDG-1000 class of US navy [1]~[4]. This newest ships have proven much higher fuel efficiency, and much less maintenance compared to the previous model-ships, but there are still difficulties in designing due to the lack of experience. In the following, the conceptual design of IPS for KDDX is presented with practical considerations based on the previous IPS ships.

II. IPS Design Concept

A. Generating power capacity of KDDX

The electric power demand of KDDX can be assumed as

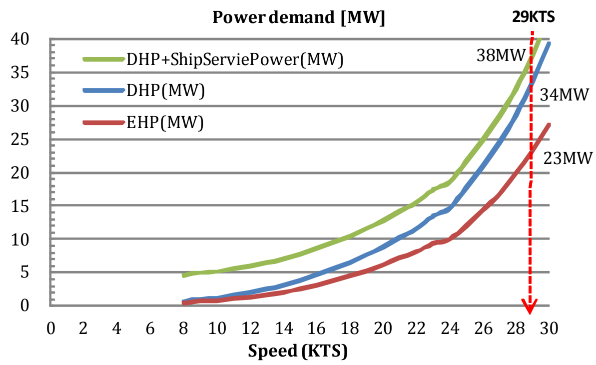


Fig. 2. Assumed electric power demand of KDDX.

shown in Fig. 2. Depending on the desired maximum speed, the required propulsion power (DHP; Delivered Horse Power is the required power to be reached at the propeller shaft) is rising steeply. The rated power of propulsion motor can be estimated by applying the efficiency of motor and variable speed drive system. Appling the conservative efficiency of propulsion motor drive system, the propulsion motor is required to produce 20MW per set in KDDX.

$$P_{motor} = \frac{P_{DHP}}{2 \cdot \eta_{motor(0.92)} \cdot \eta_{VSD(0.94)}} \qquad (1)$$

Based on electric loads analysis of the previous KDX-III class, the maximum ship service loads of KDDX are assumed as 4MW at navigation mode and 2MW at anchoring mode. To obtain 44MW of power at maximum speed, two sets of large Gas-Turbine Generators (GTGs) are basic choices due to the restricted ship space and weight limitation. The rated power of a GTG should be designed with the condition of the failure of the other GTG. Even though the largest generator is out of service, the remaining generator should support the half speed of designed maximum speed as well as all ship service loads [5]. On the other hand, one of the critical operation modes is a standby mode in the harbor or certain anchoring area. In this case, the electric loads could be a minimum. Thus, the small diesel-engine generators (DGs) are to be installed for anchoring/shore mode.

The rated active power of a GTG should support the half of total propulsion power and all ship service loads at the 90% of loading factor. Considering the power factor of loads, the capacity of GTGs and DGs in KDDX can be assumed as below Eq.(2) ~ (5).

$$P_{GTG}[MW] = \frac{P_{1PM+SS.loads@sea}[MW]}{LF_{0.9}}. \qquad (2)$$

$$S_{GTG}[MVA] = \frac{P_{GTG}[MW]}{PF_{0.95}}. \qquad (3)$$

$$P_{DG}[MW] = \frac{P_{SS.loads@harbor}[MW]}{LF_{0.9}}. \qquad (4)$$

$$S_{DG}[MW] = \frac{P_{DG}[MW]}{PF_{0.8}}. \qquad (5)$$

where, the power factor of large GTG is assumed as 0.95 and small DG is 0.8, because the power factor of the power electronic converter driving the propulsion motor would be around unity at the rated power and most of the load of GTG is the power to the converter.

B. *IPS configuration*

The conceptual configuration of basic IPS is depicted in Fig. 3. Since the total installed power is over 50MW, the output voltage of generator should be medium-voltage (MV) to reduce the phase current of distribution cable.

$$I_{rms}[A] = \frac{S}{\sqrt{3} \cdot V_{ll\_rms}}[VA/V] \qquad (6)$$

The line to line rms voltage, 6.6kV, is recommended in the IPS of KDDX, because it is commonly used in the large

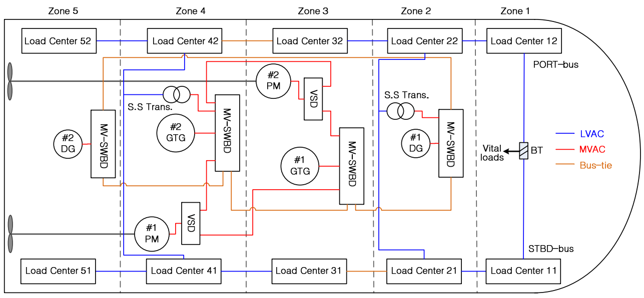


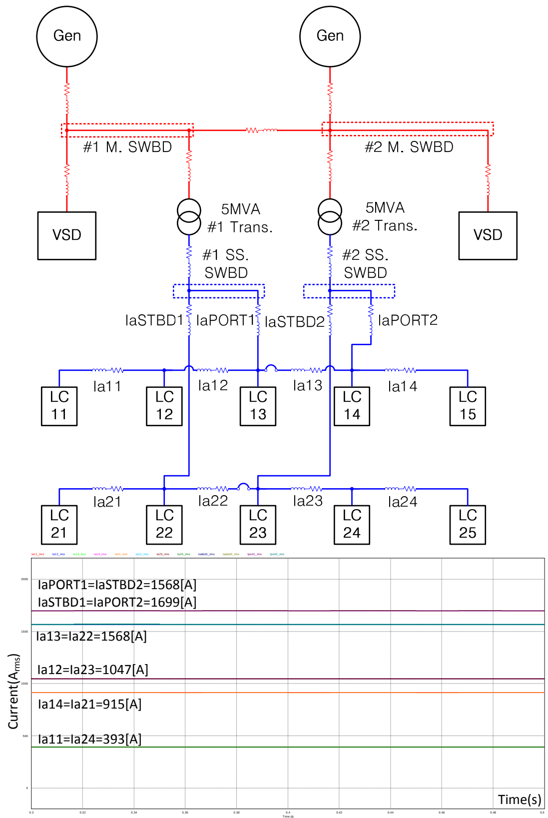
Fig. 3. Basic configuration of IPS.

commercial ship. Even if the 6.6kV is applied to the system, the phase current of a GTG would be expected around $2200A_{rms}$ according to the Eq. (6).

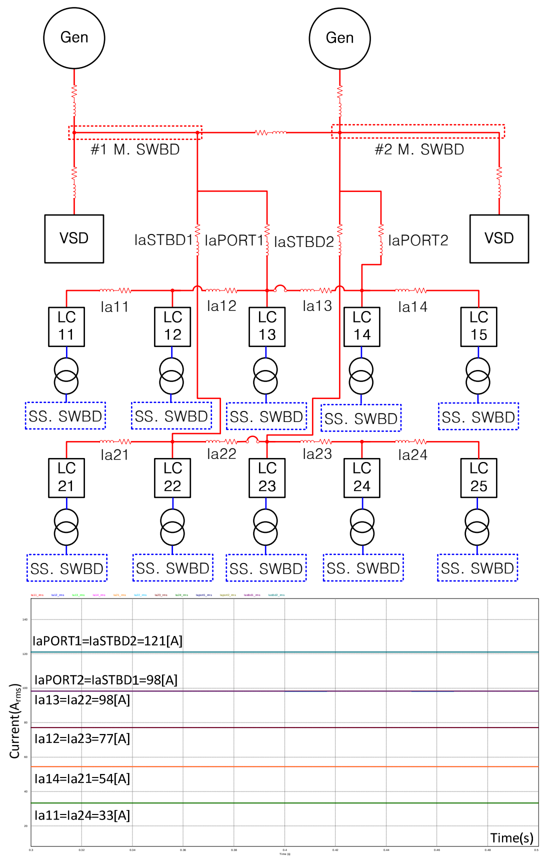
$$I_{rms} = \frac{24/0.95[VA]}{\sqrt{3} \cdot 6600[V]} = 2200[A_{rms}] \qquad (6\text{-}1)$$

All generators can be interconnected by bus-tie breaker, but normally it remains open to ensure the balanced power distribution. The propulsion motor system is connected through the MV switchboards.

The types of ship service power are mainly 440V/220V/115V of 60Hz. These loads can be divided into five electrical zones, and each zonal load is connected to the different power sources by automatic/manual Bus-Transfer devices. Depending on the distribution voltage and structure, the quantity and rating of the required ship service transformer (6.6kV/450V) can be determined.



(a) 440V Low-Voltage distribution



(b) 6.6kV Medium-Voltage distribution

Fig. 4. Comparison of LVAC and MVAC distribution.

By the conventional low-voltage distribution system as shown in Fig. 4(a), the required power rating of a ship service transformer is 5MVA. Because of N+1 policy, a transformer can support all electric loads in the case of the failure of the other transformer. Whereas, in the medium-voltage distribution system as shown in Fig. 4(b), each load center is connected by MV power cable and many smaller ship service transformer (less than 1MVA) are installed at load center. Even if one transformer fails, then other transformer can provide electricity to the load through other routes set by contactors and bus ties.

The currents on the zonal distribution-bus are compared as shown in Fig. 4. For the computer simulation, zonal cable impedance and parameters of load models are reasonably entered based on the practical ship's data. The detail parameters are given in Appendix Table I. The MV distribution can reduce the current rating of cable, but lots of transformers and LV-switchboards may be too bulky in KDDX.

Whether MV distribution or LV distribution are applied, the zonal current-capacity could be differed by the system configuration and operation concept. Therefore, after precise analysis of power flow, the rating of power cable at each section should be optimized to reduce the cable weight, especially in the case of the low voltage distribution.

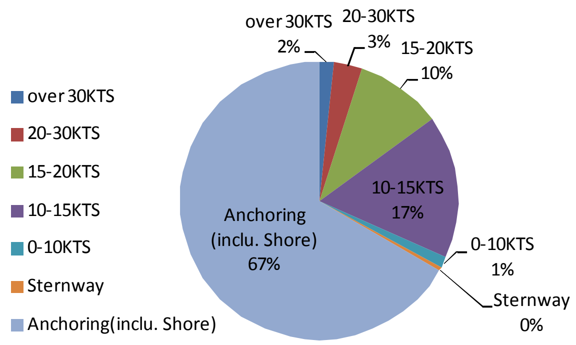


Fig. 5. Annual operation profile of a typical destroyer case.

III. IPS OPERATION ISSUE

A. Single Generator Operation

Shipboard electric power system is similar to the islanding mode of microgrid system, because the utility grid power is disconnected and all electric loads should be supported by a few shipboard gensets. The blackout caused by the generator-trip is serious to the ship mission. Thus the fail-safe operation would be preferred to the system efficiency in the view of the operating of the combat ship. In the IPS configuration of KDDX, two small diesel gensets and two large gas-turbine gensets are installed for harbor mode and navigation mode, respectively. For the higher reliability and preferred fail-safe operation, each two gensets should be always operated in parallel at harbor or during navigation. This is the Navy rule of operation of gensets, not only Korean Navy's but also other countries'.

On the other hand, the annual operation profile of a typical destroyer can be estimated as shown in Fig. 5. Even though the practical operation time can be varied by ship mission, it could be assumed that the harbor mode holds 2/3 time and navigation mode holds 1/3 time of annual time. Among the navigation time, the ship speed between 10 to 20KTS accounts for almost 80%. It means that the ship propulsion system must be designed to suit economic cruising below 20KTS. But in the IPS configuration, two GTGs are always operated in parallel. That reduces the loading factor of a GTG to a half. For example, the estimated propulsion power at 20KTS is about 10MW considering the efficiency of the motor and its drive system and the total power is less than 14MW including all ship service loads. Thus the loading factor in case of a single generator is around 60%, but it would be dropped to 30% in the case of double-generators operation. Therefore, the practical alternative to enhance the fuel-efficiency is the Single Generator Operation (SGO). The differences of Specific Fuel Consumption (SFC) and fuel consumption according to existence of the SGO are presented over all ship speed range in Fig. 6 and 7. According to the generator operation concept, this fuel-saving effect is appealing due to 40 years' life span and huge annual energy cost of the ship. Supposing the ship is cruising at 10 KTS (with assumption of 5MW consumed power) for 24-hours,

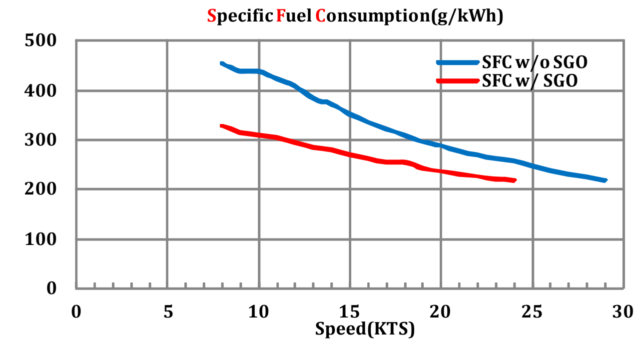


Fig. 6. SFC of each speed by applying SGO.

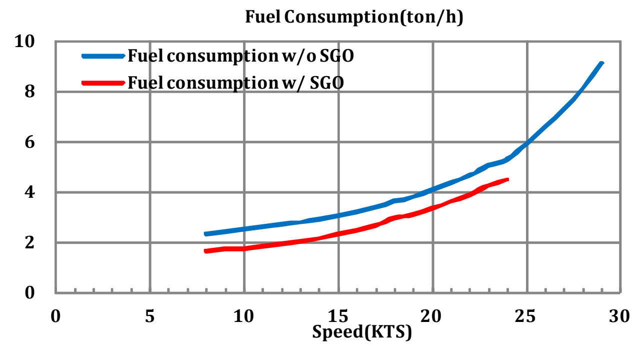


Fig. 7. Fuel-saving of each speed by applying SGO.

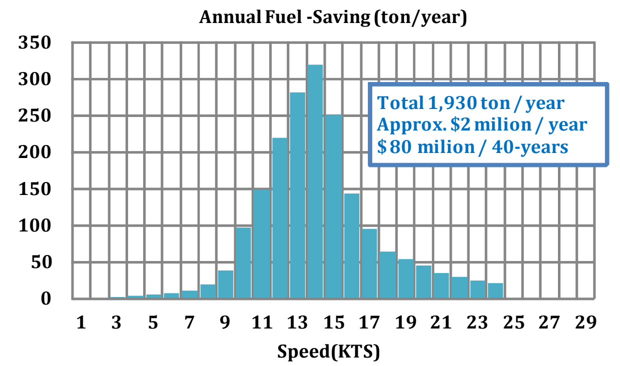


Fig. 8. Annual fuel-saving of each speed by applying SGO.

the amount of fuel-saving by applying SGO mode can be calculated as Eq. (7). And the cost of fuel-saving can be calculated as Eq. (8) based on the current oil price quoted by Korean navy.

$$(440[g/kWh]-310[g/kWh])\times 5[MW]\times 24[h]=15.6[t] \quad . (7)$$

$$(\frac{15.6[t]}{0.000845(\rho)[t/\ell]})\times 0.8[\$/\ell]=15{,}000[\$] \quad . \quad (8)$$

If applied with same calculation to overall speed range, the annual amount of fuel-saving can be obtained as shown in Fig. 8. From the result, SGO mode would be a very important design factor.

B. *Shipboard battery energy storage system*

The SGO mode has a risk of blackout at all times, which makes unacceptable operation mode for Navy crew. Therefore, shipboard energy storage system is essential for

Fig. 9. Shipboard Battery Energy Storage System of RCT system [7].

SGO mode so as to provide emergency power to both propulsion loads and ship service loads till the other generator to be synchronized to the ship's power system. The emergency power source in the conventional shipboard power system is a small dedicated emergency-generator for black-starting of the main generator. Also, the dedicated UPS and emergency batteries for vital load were all of backup power.

Recently, the large capacity of shipboard BESS draws attention [6]. With increased concern about ship service life costs, US Navy developed lithium-ion battery energy storage system to apply into the conventional generation system of DDG-51 class. The Shipboard BESS unit is packaged by the cabinet as shown in Fig. 9 and each unit is composed of battery pack module, power conversion module and battery management system. To support 3MW ship service power during SGO fail mode, 5 sets of 600 kW BESS unit is supposed to install in DDG-51 class. But this system only considered the ship service loads.

For the KDDX application, the capacity of BESS should support the propulsion motor loads as well as the ship service loads. To ensure safe operation and not to lose control for propulsion, a certain amount of propulsion power should be maintained in IPS even in the case of the failure of a GTG working as SGO mode. For the feasibility of proposed IPS with BESS, the total capacity of BESS is set as 8MW/2MWh. Where, the lithium-ion battery cell is assumed 4C-rate of discharge current, which is well proven in the practical yard of industry. The example of lithium-ion battery for shipboard power application is presented in Appendix Table II.

The BESS provides power to all electric loads with priority, and then the remaining available power is assigned to the propulsion loads. Then, at least, 4MW of propulsion power would be available, and the propulsion motor can be controlled up to nearly half of maximum speed of the ship.

IV. THE FEASIBILITY OF IPS WITH BESS

A. *The layout of IPS with BESS*

The conceptual design of total 8MW/2MWh BESS can be considered as shown in Fig. 10.

a. Layout 1: 2MW/500KWh x 4 units
(6.6kV Medium-voltage large module)

b. Layout 2: 2MW/500kWh x 4 units
(440V Low-voltage large module)

c. Layout 3: 800kW/200kWh x 10 units
(440V Low-voltage zonal module)

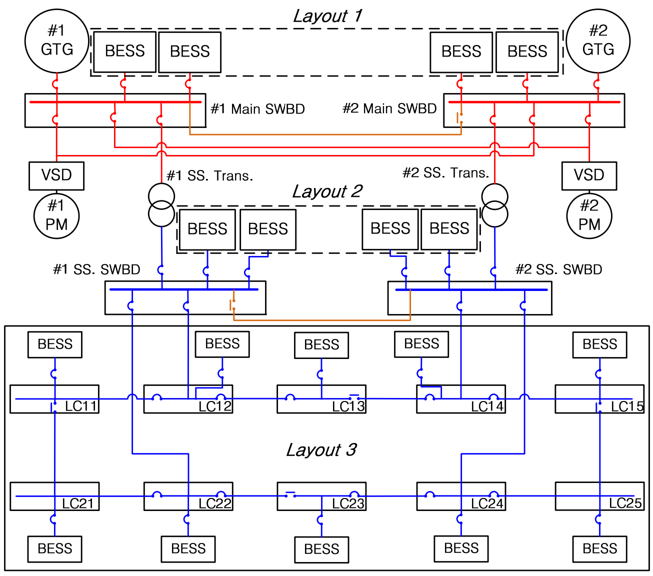


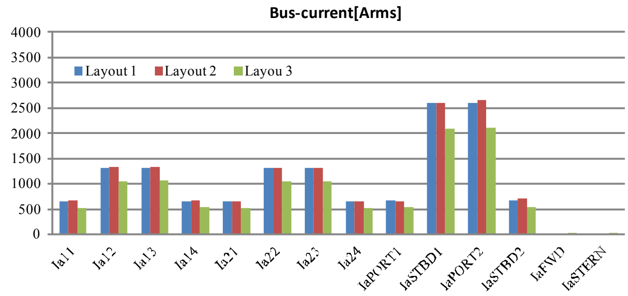
Fig. 10. Conceptual layout of IPS with BESS.

Layout 1 is a system, where BESS units are connected to the medium-voltage bus. 2MW/500kWh lithium-ion BESS is already commercialized in a container package in the field of renewable system. In this system, the step-up or isolation transformer is conventionally used with 3-level NPC converter or cascaded H-bridge converter, respectively [8]. Due to the limited ship space and weight, the bulky transformer in each BESS unit is obviously detrimental effect on system weight to KDDX.

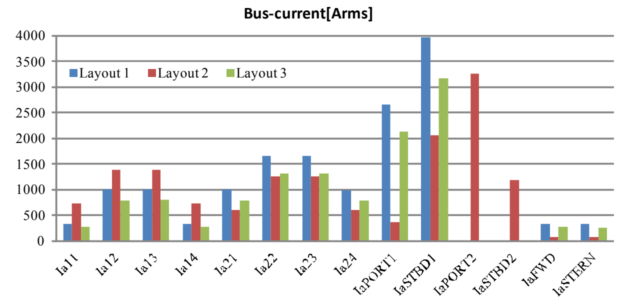
On the other hand, Layout 2 and 3 use low-voltage modules but the difference may be unit size. In these layouts, of the available power for the propulsion from BESS is transmitted to MV-SWBDs through ship service transformer. Because, in the case of BESS operation, the ship service loads are supported by the BESS, the power of the transformer to the ship service load is null, and the all capacity of the transformer can be exploited to transfer power from BESS to the propulsion load. With this design concept, the transformer can be used as dual purposes and the bulky transformer for BESS can be saved.

To verify the power flow of Layout-1, 2, 3, the computer simulation was carried out by PSIM software. The electric load at each load center is an equivalent model, which is controlled by 400kW load power with power factor (PF) 0.8. And the propulsion load is also an equivalent model, which is controlled by 2MW load power with PF 1. On the SGO backup mode, one of BESS units performs as a swing bus unit.

As shown in Fig. 11, all layouts can operate normally without any difficulties of power flow. On the failure condition of one ship service transformer, the remaining ship service transformer can manage the power between the MV-bus and LV-bus. Layout 2 and 3 seems more efficient in the condition of anchoring mode, because there is no need to support the propulsion loads. The layout 3 shows a tendency of smaller bus-currents compared to others.



(a) Normal operation



(b) On the condition of #2 Trans. failure

Fig. 11. Zonal bus-current comparison of Layout-1, 2, 3

B. *System Benefits of IPS with BESS*

The proposed IPS with BESS for KDDX has a lot of system benefits, similar to the conventional energy storage system in land-base. As well as fuel-saving, the maintenance cost would be reduced conspicuously due to the reduced operation time of the generators. Also, thanks to the improved fuel-efficiency, the crusing distance would be increased with same size of fuel tank. IPS incorporating BESS is surely a new challenge in the surface ship. But the adoption of energy storage system would be an undeniable option for the future combatant ship because of pressure to reduce the life cycle cost of the ship and to build environmentally friendly ship. Furthermore, due to the advanced pulsed weapon and combat system, where higher power density is an essential requirement, BESS can achieve much higher power density compared to not only conventional ship such as KDX III but also modern IPS such as DDG 1000. Some benefits of the proposed IPS with BESS can be summarized as follows.

a. Backup power for outage of SGO
b. Peak shaving during acceleration of the ship
c. Power quality improvement of the main bus
d. The use of regenerative power during crash-stopping
e. Power supply for future high pulsed electric loads

V. CONCLUSION

The fuel-efficiency is a crucial factor in the design of IPS. The Single Generator Operation as a practical and viable solution for the better fuel-efficiency of IPS was proven using the various ship data. To keep the reliability on the SGO mode, the shipboard Battery Energy Storage System is required as a backup power source.

The necessity and capacity of BESS has been presented in this paper. For KDDX application, the capacity of BESS should cover the limited propulsion power as well as all ship service loads. To find the optimum structure and installation of total 8MW/2MWh BESS in ship distribution system, some conceptual layouts are considered based on the simplified computer simulation. Even though the propulsion power should be supplied from the backup power, the low-voltage connected BESS is more reasonable in the point of system weight and ship service transformer dependency. In the last, the various benefits of the IPS with BESS were mentioned.

APPENDIX

TABLE I
CABLE IMPEDANCE BY ASSUMED ZONAL DISTRIBUTION

Voltage	Current	R	L
6600 V	2400 A	0.408 mΩ (20m) 1.224 mΩ (60m)	3.42 uH (20m) 10.26 uH (60m)
440 V	4000 A	0.0793 mΩ (10m) 0.3172 mΩ (40m)	0.321 uH (10m) 1.284 uH (40m)

TABLE II
SPECIFICATION OF LITHIUM-ION BATTERY CELL (SAFT VL34P[9])

	Characteristics	Value
Cell	Nominal capacity	33Ah
	Nominal voltage	3.65V (2.5V~4.1V)
	Energy	120Wh
	Maximum discharge current at 25℃	500+A
	Continuous power at 100% SOC	1250W
	Mass	0.94kg
Module	Nominal capacity	31.5Ah
	Nominal voltage	43.2V (30V~49.2V)
	Energy	1.3kWh
	Maximum discharge current at 25℃	200+A
	Continuous power at 50% SOC	20kW
	Mass	16kg

REFERENCES

[1] S. D. Sudhoff, “Currents of Change”, IEEE power & energy magazine, July/August, pp. 30-37, 2011.

[2] M. Bash, R.R.Chan, J. Crider,C.Harianto, J.Lian, J.Neely, S.D. Pekarek, S. D. Sudhoff, and N. Vaks, "A Medium Voltage DC Testbed for ship power system research," Electric Ship Technologies Symposium, 2009. ESTS 2009. IEEE, pp. 560-567, 20-22 April 2009.

[3] T. Ericsen, N. Hingorani, Y. Khersonsky, ”PEBB - Power Electronics Building Blocks from Concept to Reality”; 53rd Annual Petroleum and Chemical Industry Conference, 2006, Industry Applications Society Sept. 11 2006-Oct. 15 2006 Page(s):1 – 7

[4] R. J. Thome, E. Bowles, and M. Reed, “Intergration of electromagnetic technologies into shipboard applications,” *IEEE Trans. Appl. Supercond.*, vol. 16, no. 2, Jun. 2006

[5] ABS, Guide for Building and Classing High-Speed Naval Craft, Part 4, chapter 8. Section 5, 2007.

[6] R. E. Hebner, J. D. Herbst, A. L. Gattozzi, “Pulsed Power Loads Support and Efficiency improvement on Navy Ships”, *ASNE Naval Engineers Journal*, April, pp. 23-32, 2010.

[7] D. Mahoney, D. Longo, J. Heinzel, J. McGlothin, “Advanced Shipboard Energy Storage System, ASNE EMTS Symposium, 23-24 May, 2012.

[8] I. Trintis, S. Munk-Nielsen, R. Teodorescu, “Single Stage Grid Converters for Battery Energy Storage”, Power Electronics, Machines and Drives (PEMD 2010), 5th IET International Conference on, pp.1-6., 2010.

[9] Data sheet for the Saft VL34P - high power cell, Saft America, Inc., www.saftbatteries.com.