Consideration of Active-Front-End Rectifier for Electric Propulsion Navy Ship

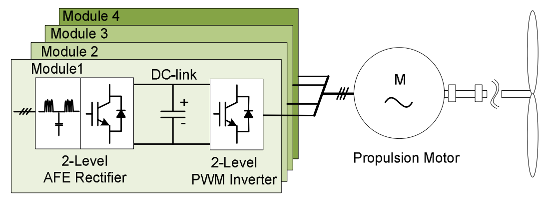
So-Yeon Kim, Byung-Geuk Cho, Seung-Ki Sul
School of Electrical Engineering and Computer Science
Seoul National University
Seoul, Korea
sykim5310@eepel.snu.ac.kr

Abstract— **This paper proposes a control strategy of an active front end (AFE) rectifier to cope with voltage deviation at the shipboard AC-power system. The voltage sags in naval ships may occur when the step load such as a large pulse power weapon is applied or when faults happen in the grid or generators themselves. In this paper, the capability of AFEs to support voltage is presented for the voltage sags. In the proposed control scheme, reactive power is utilized to achieve voltage compensation. For the verification of the effectiveness, simulation using MATLAB/Simulink and PLECS has been conducted.**

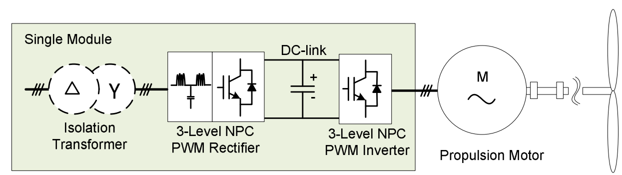
I. INTRODUCTION

In the naval shipbuilding yard, electric propulsion systems instead of conventional mechanical systems have increasingly drawn attention [1]. Due to the strict requirements for the system design of navy ships such as restricted space, reliability of power sources, redundant functionality enhancement, high quality of distribution power and etc., the design of electric propulsion system and associated shipboard power system is still challenging. Moreover, as technological developments in propulsion motor and its power electric drive system have been achieved, there are numerous combinations for the equipment selection and thus optimal configuration of power system including propulsion system is a difficult task. In general, a PWM voltage source inverter with an induction motors or permanent magnet synchronous motor is considered to be proper type of propulsion drive system for the navy ship. For the DC link power supply, 6 or 12 pulse diode front end (DFE) rectifiers with bulky transformers are normally employed.

However, recently, active front end (AFE) rectifiers vigorously replace DFEs in the naval vessel application [2]. AFE rectifiers allow bi-directional power flow and this enables regenerated power from the propulsion motors returning to the AC grid and accordingly the capacity of the dynamic breaking resistors (DBR) could be reduced or saved. In addition, almost sinusoidal input currents are injected into the ship-grid with comparatively small filters. Especially, if the low voltage system is designed, the bulky transformers can be saved and it considerably reduces the weight of the system. Furthermore, the power ratings of the main generators can be marginally reduced because the AFEs can improve the power factor. In Fig 1, typical system configuration with AFEs is depicted depending on the voltage level of the system. For the isolation and safety, a transformer might be used in medium voltage system.



(a) Low voltage (less than or equal to 690V) connected transformerless system



(b) Medium voltage (over than 100V) connected transformer-fed system

Figure 1. Typical configuration of electric propulsion drive system with AFE rectifier for navy ship.

This paper investigates the utilization of the paralleled AFE rectifiers with low voltage AC input, particularly focusing on the capability of voltage support to enhance the system-reliability for certain operating conditions. Voltage quality is one of the main concerns in the operation of the navy ship and especially grid faults or voltage fluctuation caused by the application of pulse loads complicates the integration of full electric propulsion systems. Because the total capacity of the AFE rectifiers in the electric propulsion navy ship normally approaches the entire generation power capacity, the reactive power to support the grid could be provided by AFE in the case of grid faults and any fluctuation of grid voltage. Several conditions for the voltage deviation at ship grid are considered in this paper and a voltage support scheme is proposed. The proposed control

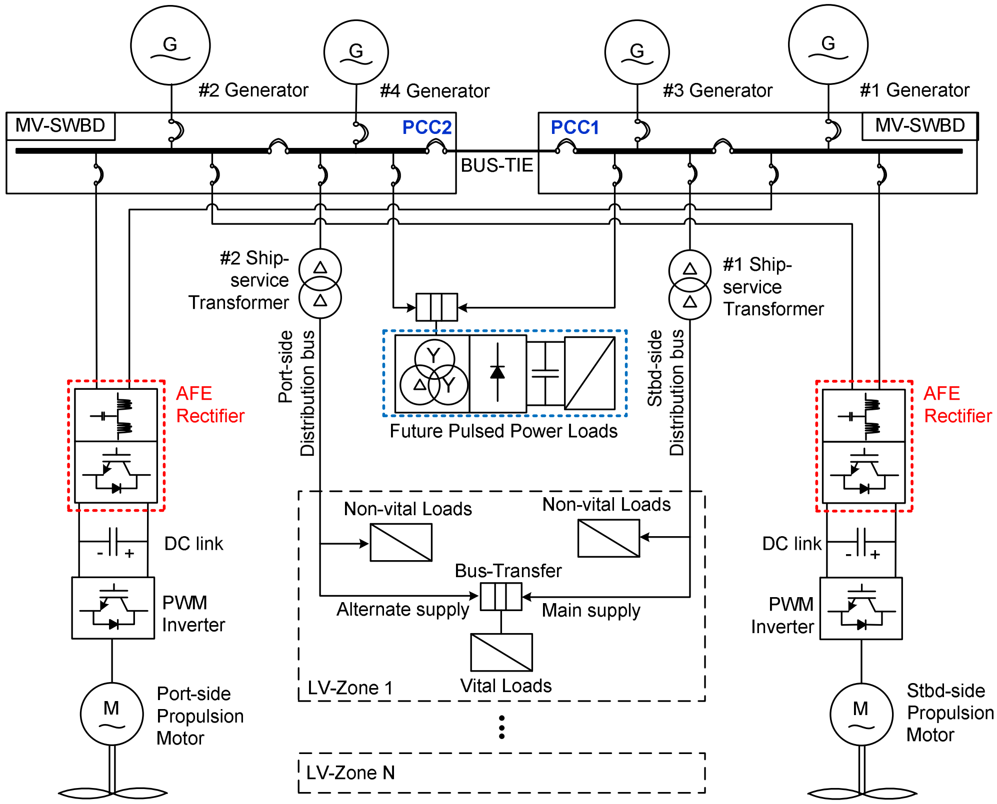


Figure 2. Simplified single line diagram of electric propulsion navy ship.

method operates regardless of the propulsion load and it restores the voltage magnitude into the normal operation boundary.

II. System Description and Modeling

A. *Power system of electric propulsion navy ship*

Figure 2 shows the single line diagram of the system dealt in this paper. The main switchboard (SWBD) is regarded as the point of common coupling (PCC). In general, AC electric power of the ship is provided by paralleled generators and is distributed throughout the ship from the main switchboards to zonal load centers and to power panels. In the case of typical naval application, at least two main AC generators are applied and it is common to install two pairs of generators with different power capacities. In the system dealt in this paper, two diesel generators of 3.15MVA and 1.25MVA consist of one generation pair and two pairs in total are implemented. Each pair of the generators is connected to the ahead and astern switchboards to enhance the redundancy and the switchboards supply the generated power to the propulsion drive systems. If one switchboard becomes out of service, the other switchboard is required to provide limited continuous power. The grid voltage is set as line to line rms 690V with 60Hz and thus two level PWM converters are considered as AFEs.

Two ship-service transformers are in charge of distribution for variety of equipment such as hotel load, communication equipment, weapon systems, and navigation systems. Particularly, the future pulse power loads such as high power laser or pulsed sonar are considered and those loads are connected to the main switchboards [3].

B. *Power system modeling*

In order to verify the validity of the AFE rectifier, it is important to accurately model the AC ship power system and to conduct simulation for the specified operating conditions. In this paper, a simplified AC power system for the electric propulsion navy ship is composed by MATLAB/Simulink for mathematical models with controllers, and PLECS circuit to compose the electric power network as shown in Fig. 3. The major sub-models are parallel operated generator sets, two sets of AFE rectifier and its DC link, traditional electrical loads, and a special high power loads.

For the modeling of the wound rotor synchronous generator, the synchronous DQ axis equivalent circuit is used as shown in Fig. 4. From the voltage equations for the field winding, damper winding, and stator windings, the field current, the damper current, and back EMF of the stator winding can be deduced as (1)~(5) [4]. Then, terminal stator voltage given as (6) and (7) can be used to implement the generator as a voltage controlled voltage source with an internal reactance.

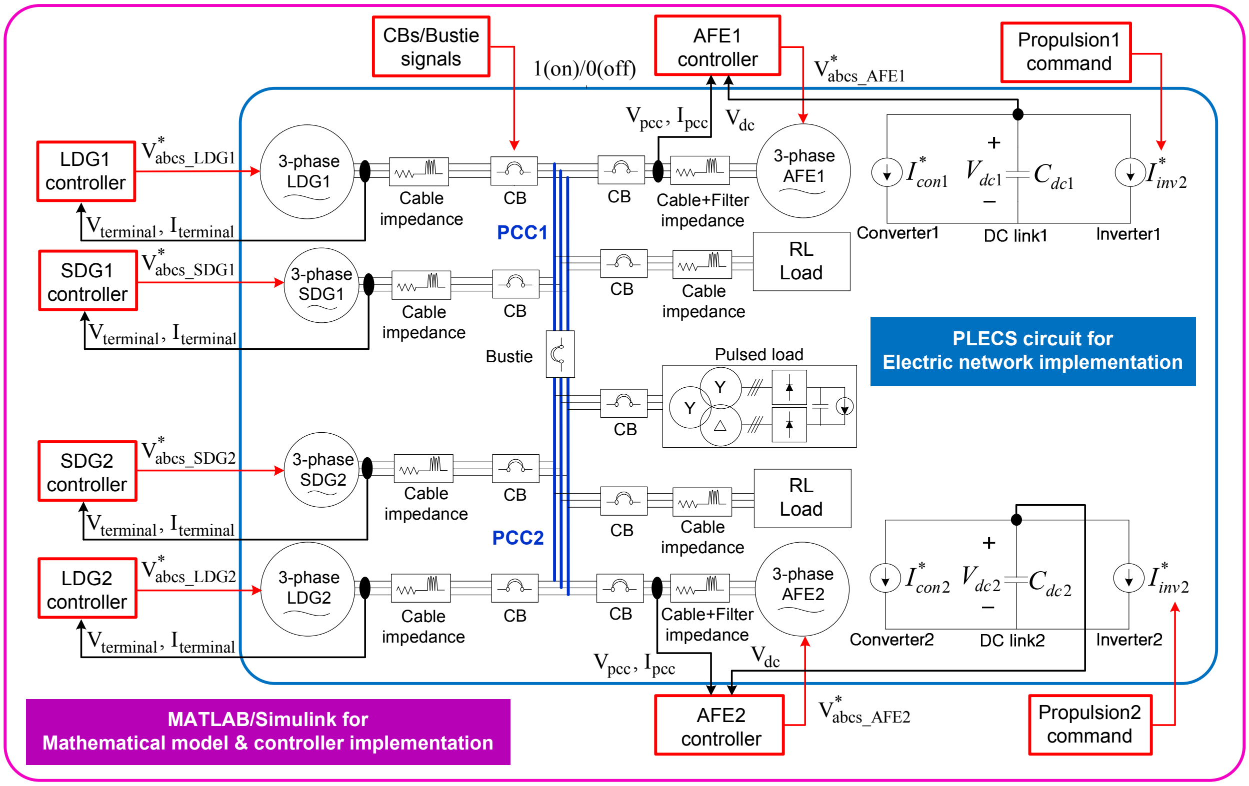


Figure 3. Simulation modeling configuration by MATLAB/Simulink and PLECS.

$$i'_{fk} = \left[\frac{s(L_{md}L'_{ldk}) + R'_{dk}}{\mathrm{A}\,s^2 + \mathrm{B}\,s + \mathrm{C}}\right]V'_{fk} - \left[\frac{s^2(L'_{ldk}L_{md}) + s(R'_{dk}L_{md})}{s(L'_{ldk} + L_{md}) + R'_{dk}}\right]i^r_{ds} \tag{1}$$

where, the capital letters of A, B, C are representing following equations;

$$\mathrm{A} = (L'_{ldk}L'_{lfk}L_{md})^2\,,\quad \mathrm{B} = (L_{md} + L'_{lfk})R'_{fk}(L_{md} + L'_{ldk})R'_{dk}\,,$$

$$C = R'_{dk}R'_{fk}$$

$$i'_{dk} = -\frac{sL_{md}i^r_{ds} + sL_{md}i'_{fk}}{R'_{dk} + s(L'_{ldk} + L_{md})} \tag{2}$$

$$i'_{qk} = \frac{sL_{mq}}{s(L'_{lqk} + L_{mq}) + R'_{qk}}i^r_{qs} \tag{3}$$

$$E^r_{ds} = -\omega\left\{L_{mq}\left(i^r_{qs} + i'_{qk}\right) + L_{ls}i^r_{qs}\right\} + sL_{md}\left(i^r_{ds} + i'_{fk} + i'_{dk}\right) \tag{4}$$

$$E^r_{qs} = \omega\left\{L_{md}\left(i^r_{ds} + i'_{fk} + i'_{dk}\right) + L_{ls}i^r_{ds}\right\} + s\left\{L_{mq}\left(i^r_{qs} + i'_{qk}\right)\right\} \tag{5}$$

$$V^r_{ds} = R_s i^r_{ds} + L_{ls}\frac{di^r_{ds}}{dt} + E^r_{ds} \tag{6}$$

$$V^r_{qs} = R_s i^r_{qs} + L_{ls}\frac{di^r_{qs}}{dt} + E^r_{qs} \tag{7}$$

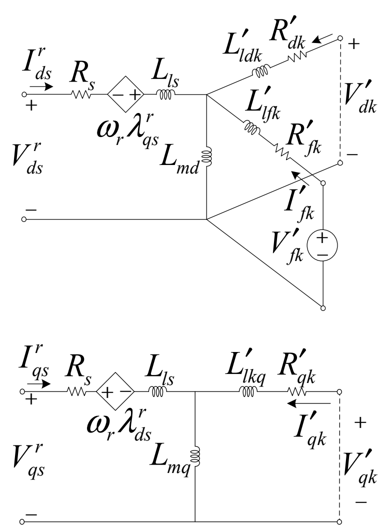


Figure 4. DQ equivalent cirfuit for wound rotor synchronous generator.

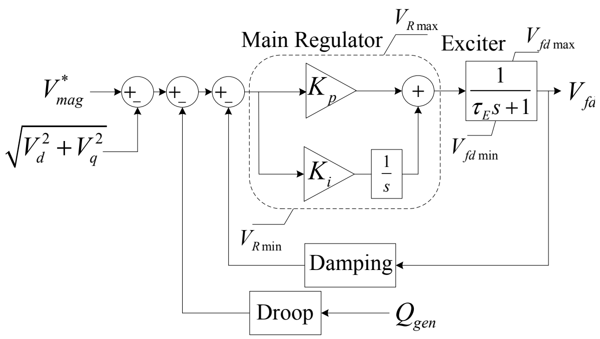


Figure 5. Block diagram of AVR.

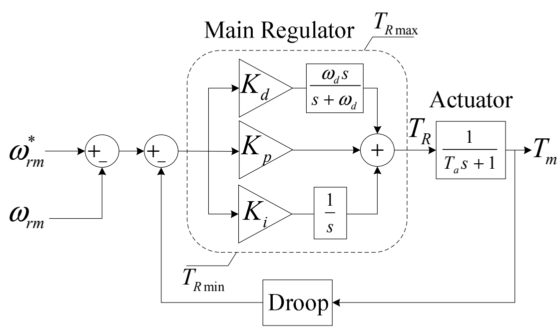


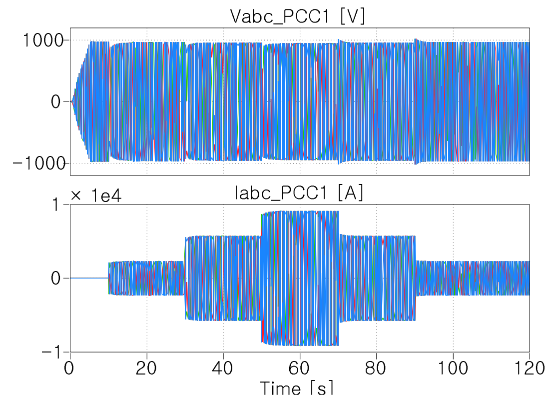
Figure 6. Block diagram of governor.

For the automatic voltage regulator (AVR) to adjust voltage magnitude, the standard IEEE type-I excitation system [5] is adopted as shown in Fig. 5, where voltage droop is implemented to achieve reactive power sharing among the generators.

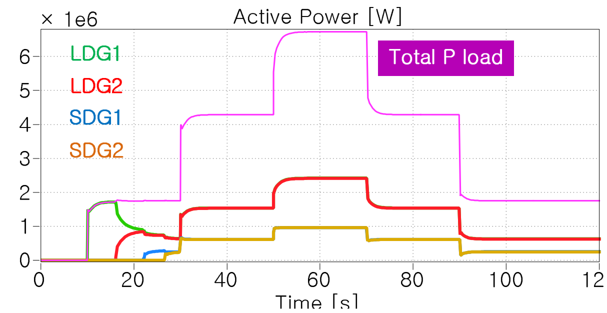
For the modeling of the prime mover and its speed regulator (governor), the electromechanical equations and PID controller is used as shown in Fig. 6, where frequency droop is implemented to share active power among the generators. The specific values for each variable are given in appendix.

To verify the validity of the models, the performance of the paralleled generators with an adjustable RL load bank has been evaluated and the results are shown in Fig. 7. As the droop slope for frequency and voltage is set according to each rated power of the generators, the load sharing of active and reactive load power can be accomplished properly. Small error in reactive power sharing is caused by different cable impedances.

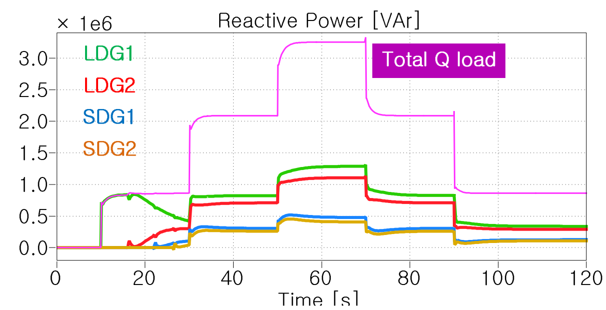
For the modeling of the power conversion devices, the PWM switching of the AFE rectifier and the inverter for the propulsion motor drive is neglected because the time constant of the power system in the ship grid is much larger than the PWM switching period. Instead, the equivalent circuit is used for the modeling of power flow at DC link. Two current sources are connected to the DC link, representing the current from the AC grid through AFE and



(a) 3-phase line to line voltage and line current at switchboard



(b) Active power of parallel generator sets



(c) Reactive power of parallel generator sets

Figure 7. Load power sharing of generator sets in parallel mode.

the one to propulsion motor through the inverter, respectively.

The controller for the AFE rectifier is composed of DC link voltage control in the outer loop and current control in the inner loop as shown in Fig. 8.

For the modeling of the future pulsed load, a charging circuit through 12-pulse diode rectifier is used with DC current source. The ship service loads including ship service transformers are simply modeled by two RL load banks.

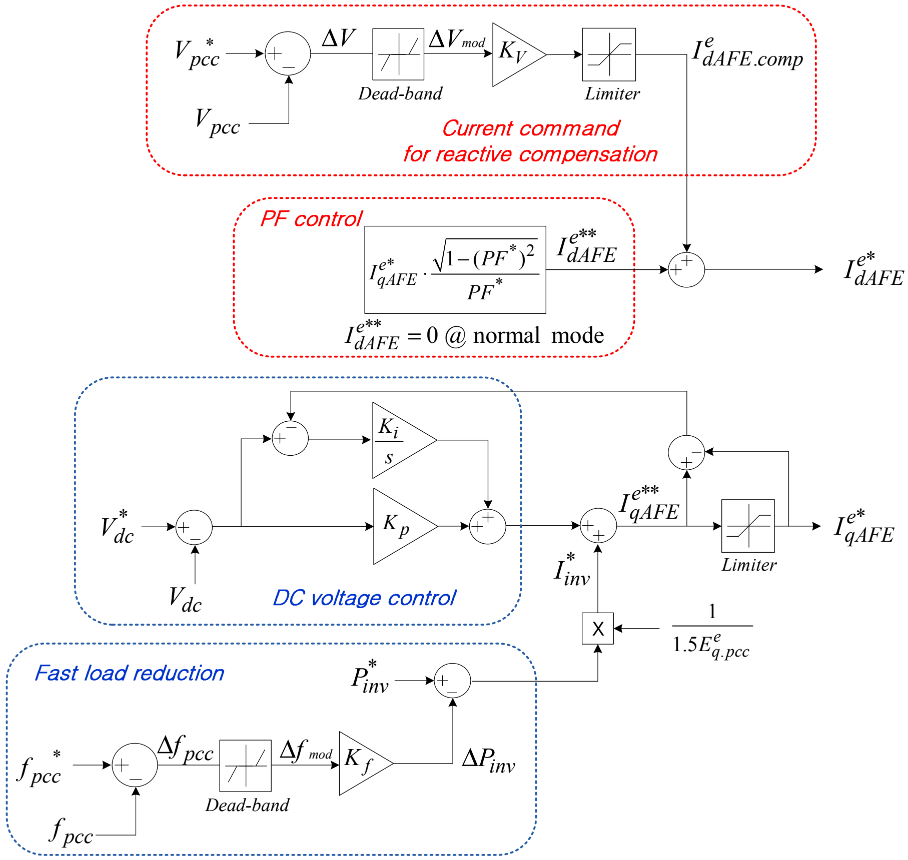


Figure 8. Block diagram of AFE rectifier control command.

C. Voltage regulations issues in naval shipboard power system

The voltage distribution is one of the main problems in shipboard power system. It usually happens when heavy load is suddenly engaged or removed in the power system or when short circuit faults occur. The international standard such as IEEE practice defines the normal voltage conditions. For the naval ship in this paper, military standard [6] is applied and the allowed voltage tolerance of AC grid in the steady state is +/-5% and transient tolerance of duration within 2 seconds is +/-16%. When the grid voltage is out of this limit, the system is considered to be in an abnormal condition.

III. Voltage Support Control Scheme for AFE Rectifier

Commonly, the reactive current command for the AFE rectifier is decided by desired power factor (PF) and unity PF is usually preferred for loss minimization. However, from a voltage support point of view, voltage compensation is achievable by varying PF as the voltage magnitude is adjusted by droop control of reactive power. Therefore when the voltage deviates from the normal condition, reactive current needs to be injected to support the grid voltage.

In the proposed controller shown in Fig. 8, the grid voltage at PCC is measured and the error from the nominal voltage value is calculated. To guarantee the continuous operation when the voltage is within the standard boundary, dead band of +/- 5% tolerance is applied to the error as shown in Fig. 9. Then the error is input to the P controller, which generates the final reactive current command. P

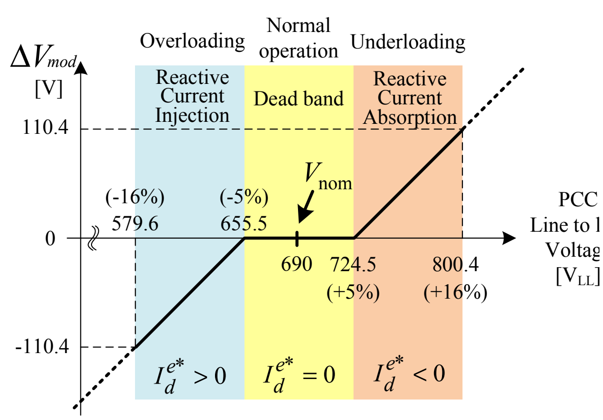


Figure 9. Voltage support mode of AFE rectifier.

controller is used to achieve fast dynamic performance and respond to the abnormal condition in a sufficiently short time period. The P gain, $K_{v,}$ is set based on (8), (9) and the value 0.16 used in the denominator makes that the available maximum current of AFE is generated at the maximum transient variation.

$$I_{dAFE}^{e*} = K_V \cdot \Delta V_{\text{mod}} \tag{8}$$

$$K_V = \frac{I_{dAFE\,\max}}{(0.16 \times E_{pcc})} \tag{9}$$

For the active current control, the propulsion load shedding scheme is included to cope with the frequency deviation. For the active power compensation due to the deficiency of generation power, energy storage system might be considered to support the grid for a few minutes [7]. In this paper, the reactive current control for the voltage support is only considered.

IV. SIMULATION RESULTS

The behavior of the system with the proposed control strategy is verified with the two case studies, namely, pulse load engagement and short circuit fault in either generators themselves or grid.

A. Pulse load engagement

In Fig. 10, the effect of a single pulse load is demonstrated. For the implementation of the pulse load, high power laser is considered and its required energy is obtained from [8]. The peak power demand of the load is 5MW, and the pulse with slew rate of 10MW/s (5MW/500ms) and duration of 1.5 seconds is engaged. When the voltage compensation is deactivated, the voltage drops to 574V which is deviated by -16.8% from the nominal value. However, if the proposed controller is employed, the voltage drops to 619V and this shows that the voltage level is improved by 7.9%. Unfortunately, the voltage is still out of the standard boundary. If further improvement is required, the application of the energy storage system should be considered [9].

B. Short circuit fault

The line to line fault at the feeder line is implemented and the result is shown in Fig. 11. As expected, the voltage drops to 568V when no compensation is made whereas the voltage drops to 619V when the proposed controller is applied. Without compensation, the voltage is out of the standard boundary but compensated voltage is in boundary. In general, fault-induced short circuit current is cut off by circuit breaker with dedicated duration and current rating. In this simulation, the fault is cleared after one second but the clearance could be delayed if the short circuit current is not much larger than the rated current of the circuit breaker. The proposed control can maintain the grid voltage as possible as high and results in larger fault current, and it activates the circuit breaker trip faster.

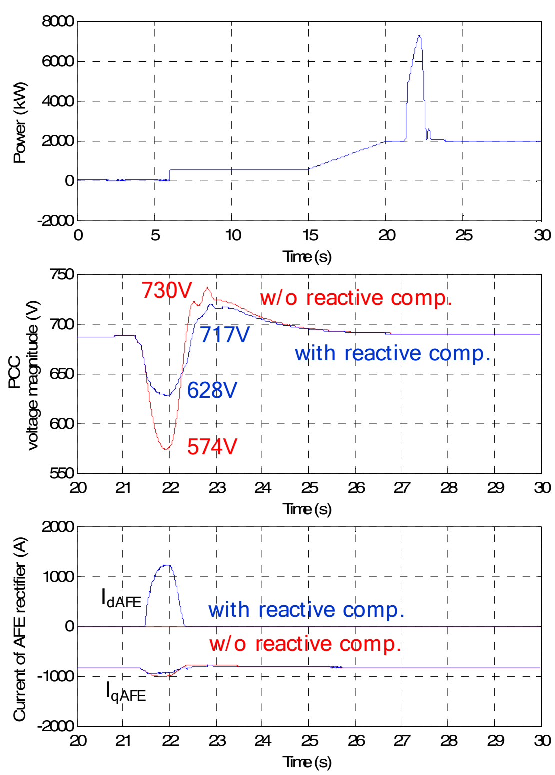


Figure 10. Pulse load employment and voltage compensation.

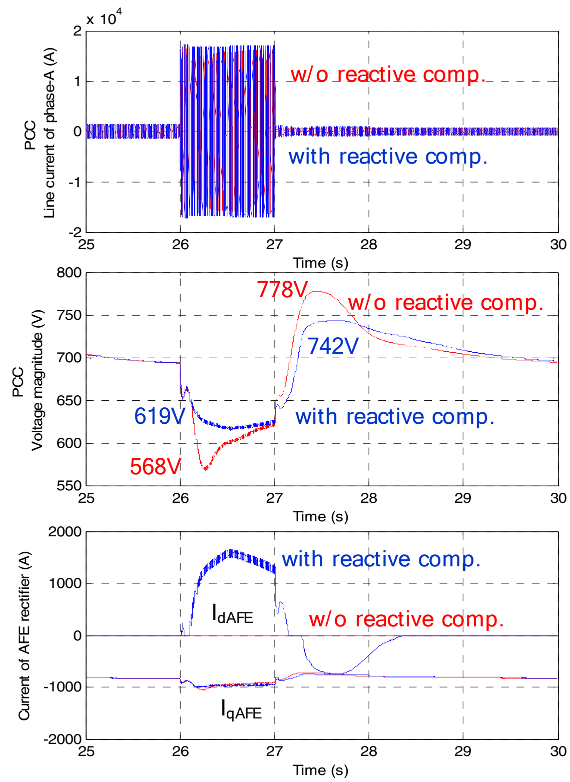


Figure 11. Short-circuit fault and voltage compensation.

V. CONCLUSIONS

This paper has proposed a reactive current injection scheme to support grid voltage of the shipboard power system through the control of AFE. The function of the AFE has been investigated and it is shown that the proposed controller is effective in response to the abnormal grid voltage conditions. In the pulse load operation, the voltage sag has been improved by 7.9% while 7.3% in the case of the line to line fault condition. The validity of the proposed controller has been tested by MATLAB/Simulink and PLECS simulation tools.

APPENDIX

Reference navy ship
4000 ton class, maximum ship speed 20 kts
AFE rectifier

$R_i = 1.9[m\Omega]$, $L_i = 200[\mu H]$, $C_{dc} = 0.01[F]$,

Bandwidth of current controller: 200 Hz
Bandwidth of voltage controller: 5 Hz

LDG data

$S_{rated} = 3.125[MVA]$, $R_s = 0.00128[\Omega]$, $L_{ls} = 53[\mu H]$,

$L_{md} = L_{mq} = 800[\mu H]$, $R'_{fk} = 0.003[\Omega]$, $L'_{lfk} = 57[\mu H]$,

$R'_{dk} = R'_{qk} = 0.0108[\Omega]$, $L'_{ldk} = L'_{lqk} = 15[\mu H]$,

$J_{LDG} = 656[kg \cdot m^2]$, $Number\ of\ poles = 8$

SDG data

$S_{rated} = 1.25[MVA]$, $R_s = 0.0034[\Omega]$, $L_{ls} = 105[\mu H]$,

$L_{md} = L_{mq} = 2900[\mu H]$, $R'_{fk} = 0.003[\Omega]$, $L'_{lfk} = 145[\mu H]$,

$R'_{dk} = R'_{qk} = 0.024[\Omega]$, $L'_{ldk} = L'_{lqk} = 60[\mu H]$,

$J_{SDG} = 100[kg \cdot m^2]$, $Number\ of\ poles = 4$

Block Diagram of Automatic Voltage Regulator

$K_{p\mathrm{LDG}} = 0.1$, $K_{i\mathrm{LDG}} = 0.1$, $\tau_{E\mathrm{LDG}} = 0.002$,

$K_{p\mathrm{SDG}} = 0.2$, $K_{i\mathrm{SDG}} = 0.2$, $\tau_{E\mathrm{SDG}} = 0.001$,

$V_{R\max} = E_{fd\max} = 10$, $damping: \dfrac{0.001s}{0.1s+1}$

Block Diagram of Governor

$K_{p\mathrm{LDG}} = 30$, $K_{i\mathrm{LDG}} = 40$, $\omega_d = 100$,

$K_{d\mathrm{LDG}} = 0.05$, $T_{a\mathrm{LDG}} = 0.15$, $K_{p\mathrm{SDG}} = 60$, $K_{i\mathrm{SDG}} = 40$,

$K_{d\mathrm{SDG}} = 0.05$, $T_{a\mathrm{SDG}} = 0.15$, $T_{R\max} = 100$, $T_{R\min} = 0$,

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