

Fuzzy based Hybrid SMES/Battery system for Stability Improvement of DC Power Systems in an All-Electric Ship

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Abstract: As the capacity of all-electric ships (AES) increases dramatically, the sudden changes in the system load may lead to serious problems, such as voltage fluctuations of the ship power grid, increased fuel consumption and environmental emissions. This paper proposes Fuzzy based Hybrid Energy storage system for improving the stability of AES. In this method the Fuzzy controller is used to control the battery DC/DC controller output. The proposed method is tested on standard test system and results compared with three control strategies (without ESS, with ESS, with HESS). Results demonstrated that the proposed controller showing good performance during the pulse load periods. By supplying the pulse loads from the fuzzy based HESS, the system maintained the voltage at the targeted level, keeping the motor at the required speed and maintaining constant generation output power both with and without pulse loads.

Keywords: pulse load. Hybrid Energy Storage System (HESS), All Electric Ship (AES), Energy Storage System (ESS).

I.INTRODUCTION

As the capacity of all-electric ships (AES) increases dramatically, the sudden changes in the system load may lead to serious problems, such as voltage fluctuations of the ship power grid, increased fuel consumption and environmental emissions. The maritime sector has a significant role in the transportation sector. About 80% of goods are carried by ships [1]. All transportation sectors (road, air, sea, rail, etc.) are responsible for around 20% of total primary energy consumption and 24% of total global emissions in the world [2,]. In addition, shipping is responsible for about 4.5% of total energy use and for 3% of carbon dioxide (CO₂), 11% of nitrogen oxide (NO_x), and 4% of sulfur oxide (SO_x) emissions of global anthropogenic emissions in the transportation sectors [3-5]. As the capacity of the AES is expected to reach hundreds of megawatts in the near future [6-7], a high-performance power system with multiple power sources is required to meet such huge power demands. The AES has different types of loads, including propulsion loads, ship service loads and pulse loads, such as electrical weapons. Electrical weapons rely on stored energy to attack targets, which need a high amount of power in a short period.

On the AES design, one of the most important features is the ramp-rate of the generators. The ramp-rate is the increased or decreased rate of the output power per minute and usually in MW/minute. The ramp-rate of ships' generators, such as gas-turbine generators are in the range of 35 to 50 MW/minute, whereas the pulse loads required a 100 MW/second ramp-rate, which is significantly higher than the ramp-rate of the generators [26], [27]. If the changes in the loads are faster than the ramp rate of the generators, unbalanced power between loads and generators occurs, which leads to instability in the power system. Because the ramp-rate of the ship's generators is not high enough to maintain the power demanded by electrical weapons, the need for an integrated power system (IPS) architecture is inevitable. The IPS is intended to provide the total amount of power required by the AES by using common set of sources [28]. Missions that require high power support, such as a weaponry system and improve the efficiency of propulsion, which are some of the advantages of the use of an IPS in ships [29]. IEEE 1709 recommends the use of medium-voltage DC (MVDC) in shipboard power systems, which improves the reliability, survivability and power quality of the system [30].

The hybrid SMES/Battery has been proposed for railway substations by using fuzzy control [31]. The use of the SMES was proposed in a hybrid vehicle in which a cryogenic tank already existed [32]. A SMES/Battery hybrid energy storage system (HESS) was integrated into micro grids to mitigate the influence of the renewable generations [33]. The implementation of a HESS for AESs has been proposed to supply both the peak and pulsed loads. Several studies were performed to mitigate the effects of the pulse loads on shipboard power system by using HESS. A super capacitor and batteries were combined to supply pulse loads and support grid stability with different control schemes [34], [35]. A flywheel energy storage system was added to the system to maintain the health of the ship's power systems by maintaining the propulsion motor speed and the generator speed during pulse load periods [36].

II.MODEL ANALYSIS

Fig.6 shows the simplified block diagram of test system (AES). For generating electrical output in AES two generators are installed and these two generators are connected to DC bus with the help of AC/DC converters. Weaponry system on AES is represented as pulse load. Modelling of test system can be done as on-board generation, electric propulsion and hybrid energy storage system.

2.1 ON-BOARD POWER GENERATION

There are several constraints on power generated by generators, including power equilibration limits, limits of the generator's active power, and the ramp-rate limits [40], [41]:

$$\sum_{j=1}^G P_{ij} = P_{Di} + P_{Li} \quad (1)$$

$$P_j^{\min} \leq P_{ij} \leq P_j^{\max} \quad (2)$$

$$\frac{P_i(n) - P_i(n-1)}{\Delta t} \leq k \quad (3)$$

where $i=1,2,3,\dots,n$, $P_j^{\min}$ and $P_j^{\max}$ are the upper and lower allowable active power outputs of generator j , respectively. $P_i(n)$ and $P_i(n-1)$ are the output power of the generator in two different moments Δ , and k is the allowable ramp-rate of the generator. Because the pulse load requires a high amount of power in a short period, and the ramp-rate of the generator cannot maintain it, the HESS is implemented in the system to supply this load. In our model, two diesel generators, 7 MW, 6.6 kV and 50 Hz, are modeled to generate power for the simplified AES.

2.2 ELECTRIC PROPULSION MOTOR

There are several constraints on power generated by generators, including power equilibration limits, limits of the generator's active power, and the ramp-rate limits [40], [41]:

In this system, a synchronize motor is used as the electric propulsion motor. The propeller is connected directly to the synchronize motor. The mechanical load power of the motor is represented in (4):

$$P_{mec} = 2\pi n Q \quad (4)$$

Where n represents the propeller rotational speed and Q is the torque of the propeller. The relationship between the supply frequency and the motor speed can be expressed as:

$$n = \frac{120 \times f_r}{P} \quad (5)$$

where n represents the propeller rotational speed, f_r is the supply frequency and P is the number of motor poles. The power capacity of the propulsion motor is 2800 hp (≈ 2 MW).

2.3 HYBRID ENERGY STORAGE SYSTEM

The stored energy of SMES is calculated as follows:

$$E_{smes} = \frac{1}{2} L I^2 \quad (6)$$

The design of the battery and SMES are based on the ship loads. There are three different types of load on the AES; 7 MW static load (ship service load), 2 MW motor load and 5 MW pulse loads. During the normal operation, the ship service load and the motor load are applied to the system with a total power demand of 9 MW. During the pulse load periods, the demand rises by 5 MW to a total of 14 MW. The battery capacity is Calculated by (7) at 13.88 kWh to cover the requirements of the pulse loads demand and to maintain the battery SOC constraints:

$$Battery_{Cap} = \frac{Pulseloads \times Time(hours)}{SOC - (UpperCont. + LowerCont.)} \quad (7)$$

III .ENERGY STORAGE CONTROLLERS

3.1 THE SMES DC/DC CONTROLLER

The SMES system is shown in fig.1 and consists of super capacitor, two combinations of diodes and MOSFETs. Charging, dis-charging and stand-by- mode are the three operating modes of SMES.

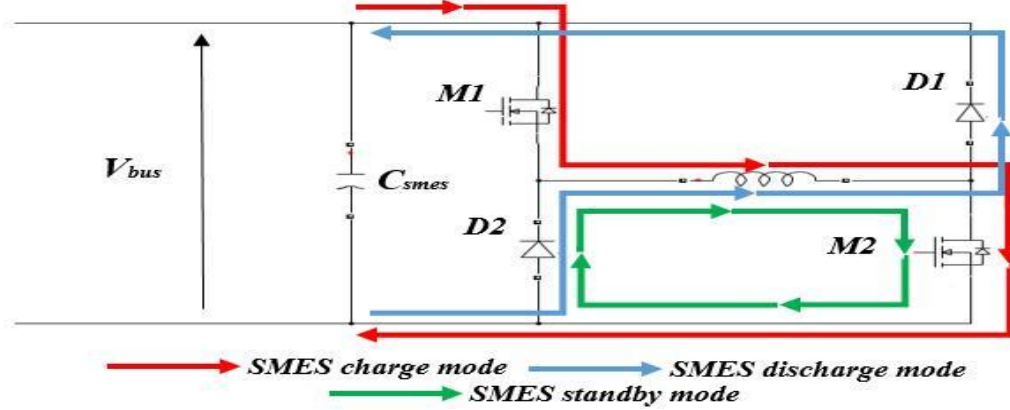


Fig.1 The DC/DC H-bridge converter of SMES with three operation modes.

3.1.1 ($V_{bus} > V_{ref(max)}$) Charge mode

Fig.2 and fig.3 shows the charging mode and Dis-charging modes of SMES DC/DC H bridge controller respectively.

$$q = (K_a) \times e^{\frac{I_{smes} \times k_b}{K_{smes}}} \quad (8)$$

Where I_{smes} is the amount of the stored current in SMES, K_a , K_b and K_{smes} are adjustable parameters that control the transition period between SMES and the battery based on I_{smes} .

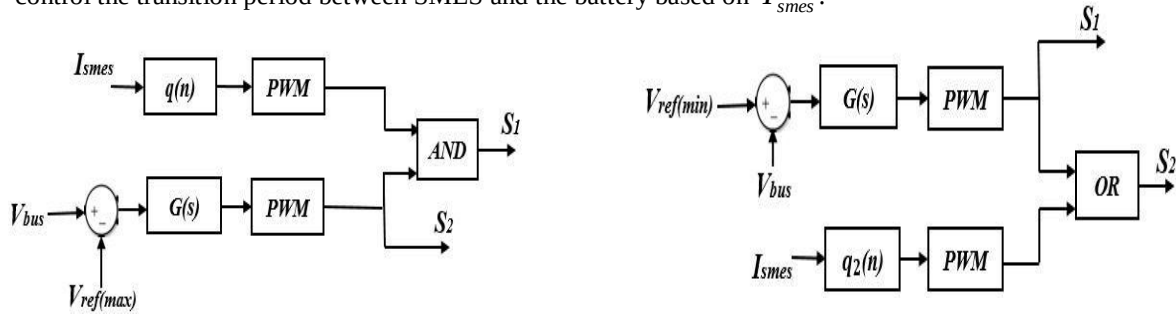


Fig. 2 & 3. Block diagram of the H-bridge DC-DC converter controller (charge mode & discharge mode).

3.1.2 ($V_{bus} < V_{ref(min)}$) Discharge mode

Discharging mode of SMES controller is shown in fig.3, in which error of voltage applied to PWM and SMES current applied to another PWM and these two outputs are connected to a OR gate. The output of OR gate is activated if any one of the input is high.

$$q_2 = (K_a) \times \log_{10} \frac{I_{smes} \times k_b}{K_{smes}} \quad (9)$$

Where I_{smes} is the amount of the stored current in SMES, K_a , K_b and K_{smes} are adjustable parameters that control the transition period between SMES and the battery based on I_{smes} .

3.1.3 ($V_{ref(bus)} > V_{bus} > V_{ref(min)}$) Stand-by- mode

In standby mode, the bus voltage is in the acceptable range between 0.97 and 1.03 p.u of the nominal voltage. Hence, no out-put current from SMES is needed. To keep the current circulating between D2 and M2, d1 is off and d2 is on.

3.2 THE BATTERY DC/DC CONTROLLER

The half bridge DC/DC bidirectional converter based on the PI controller is used to control the battery charge and discharge. The converter consists of two IGBTs, Q1 and Q2, as shown in Fig. 4.

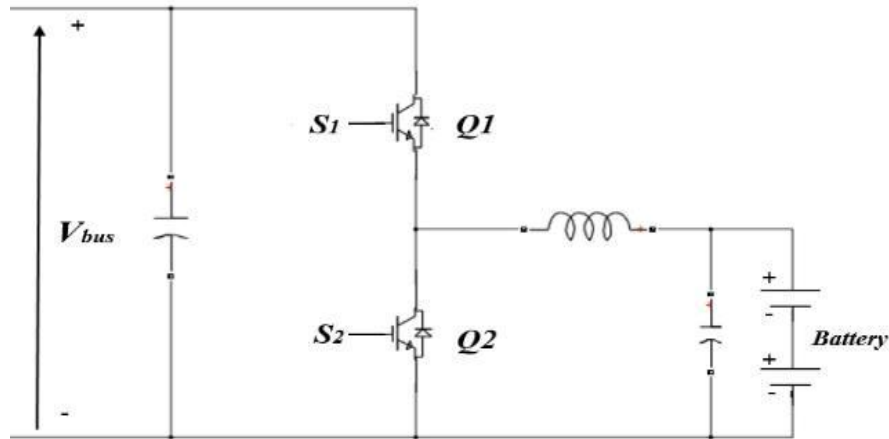


Fig. 4. DC/DC bidirectional converter based on PI controller.

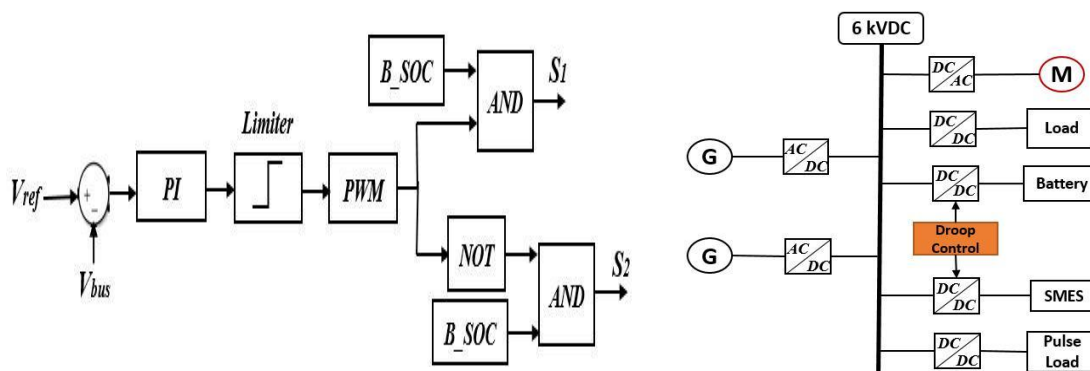


Fig. 5 & 6. Block diagram of the battery DC/DC converter controller and test system

IV.FUZZY BASED HESS SYSTEM (PROPOSED METHOD)

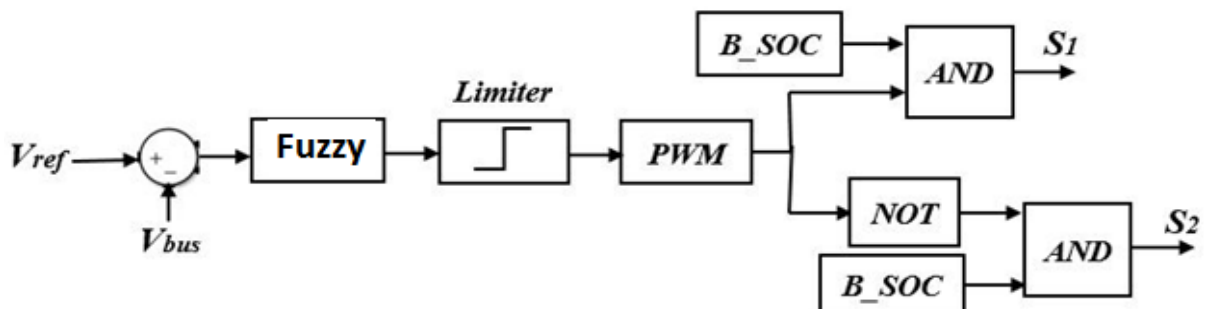


Fig.7 Block diagram representation of proposed method.

In this method, Fuzzy logic controller is applied to Battery DC/DC controller of HESS system to improve the stability. The proposed method block diagram is shown in fig.7. proposed controller input and output membership functions are shown in fig.8.

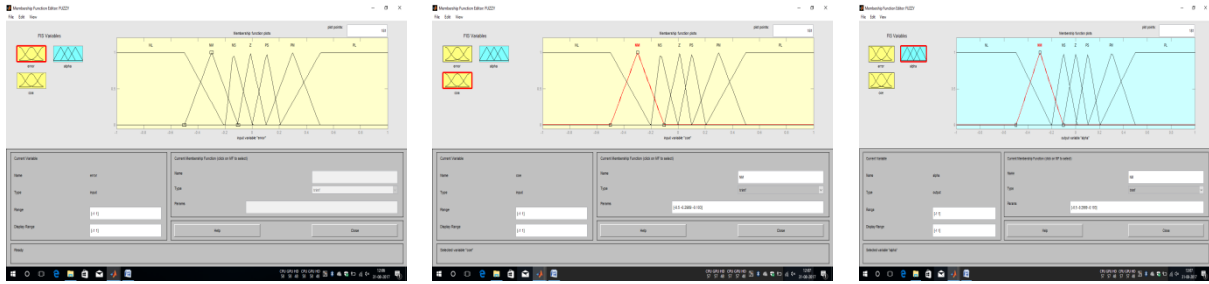


Fig.8 Fuzzy logic based controller input and output membership functions.

The error of ref and actual bus voltage is the first input to fuzzy controller and its differential is the second input. Both the inputs are divided into 7 membership functions, therefore we can write 49 rules. The input membership functions are named as negative big (NB), negative medium (NM), negative small (NS), zero (Z), positive small (PS), positive medium (PM) and positive Big (PB). Similarly output membership functions are also named. Rules and rule viewer is shown in fig.9.

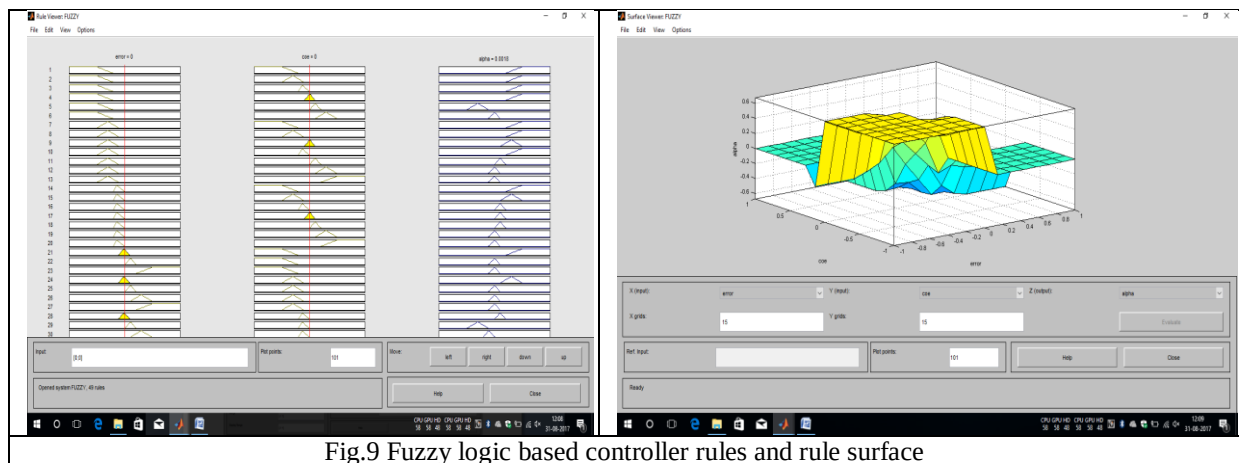


Fig.9 Fuzzy logic based controller rules and rule surface

IV . TEST SYSTEM & RESULTS

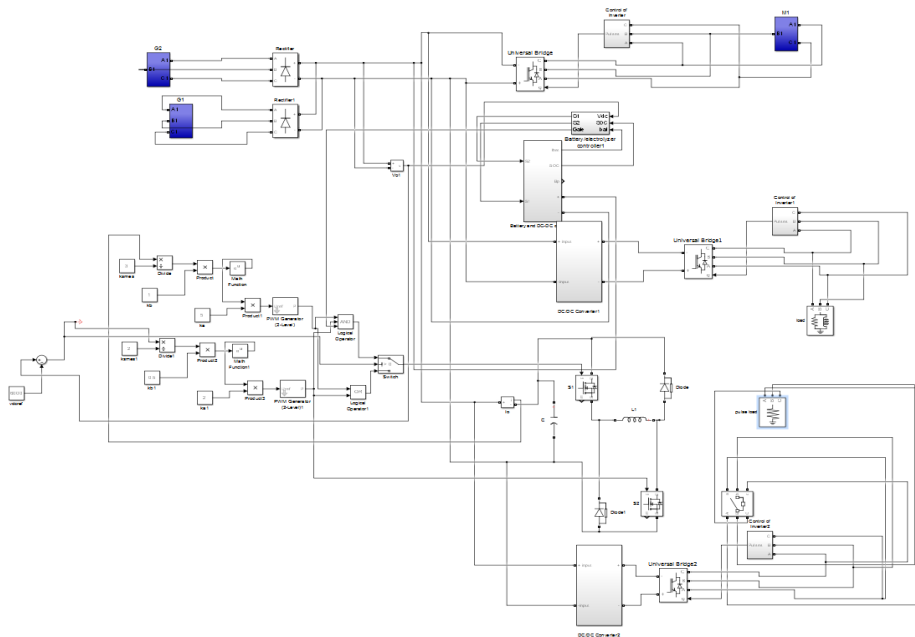


Fig.10 simulation diagram of test system with proposed controller.

The simulation results demonstrated that the Fuzzy based HESS on the dynamic droop control showed good performance during pulsed load periods, maintaining the main bus voltage at the required range and keeping the motor at the targeted speed. The system was subjected to pulse loads between $t=4.0-7.0s$ and between $t=10.0-$

13.0s. With the Proposed controller, the minimum total generators capacity is 9 MW. However, without the HESS the minimum total generators capacity is 14 MW and with HESS is 10MW. The voltage of the main DC bus was 6 kv DC according to the IEEE standard [7].

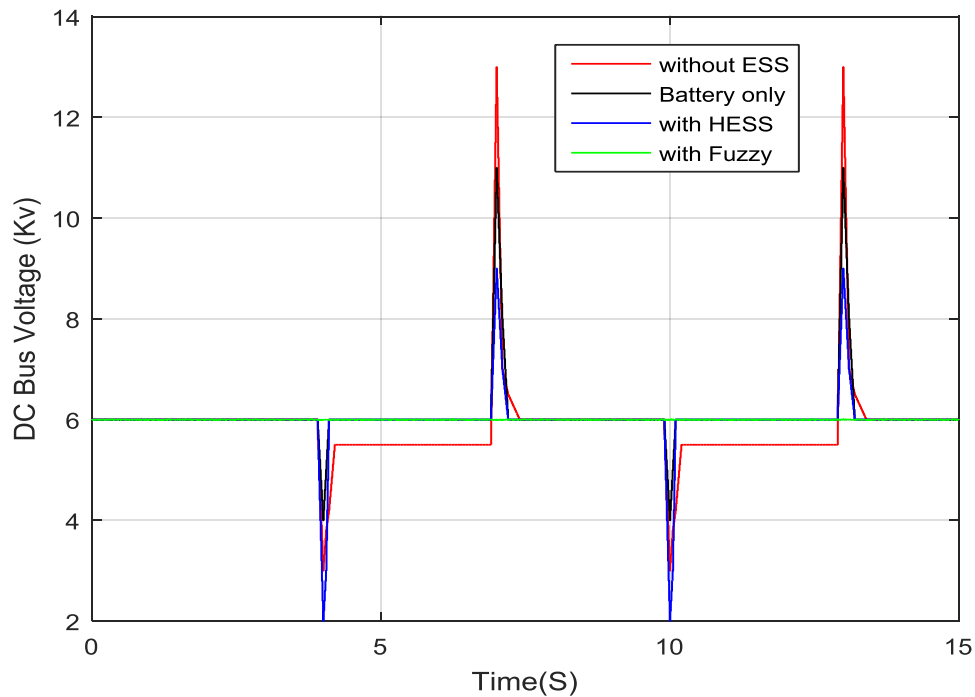


Fig.11 The DC bus voltage without ESS, battery only system, with HESS and with proposed method..

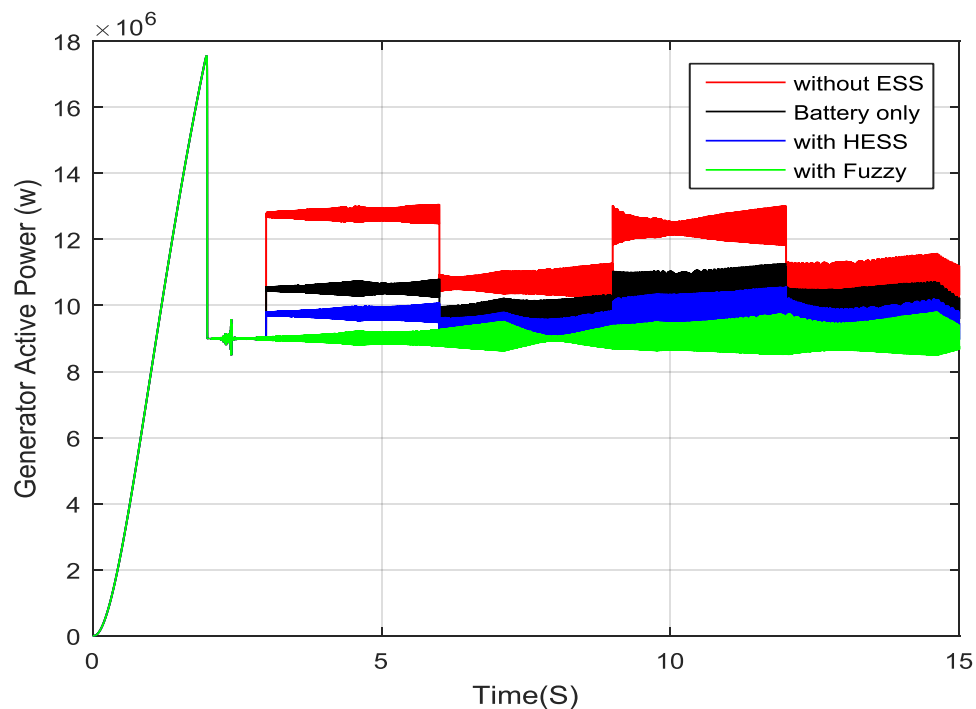


Fig. 12. The total power generation without ESS, with battery only, with HESS and with proposed method.

Fig.11 shows the DC bus voltage with three type's controllers. From this without ESS the maximum voltage is 13kv and minimum voltage is 2kv. With battery alone 11kv is maximum and 3kv is minimum voltage, with HESS 9kv is maximum and 4kv is minimum voltages of DC bus. From fig.11 it is clear that the voltage of DC bus is maintained at 6kv with small variations using fuzzy based HESS (proposed method). Therefore the proposed method is maintaining the stable voltage almost at any time with disturbances.

Fig.12 shows the generator active power with three type's controllers. From this without ESS the maximum active power is 13MW and minimum voltage is 11MW under steady conditions. With battery alone 11MW is maximum and 10MW is minimum active power, with HESS 10MW is maximum and 9.5MW is minimum active powers of Generator. From fig.12 it is clear that the generator active power is maintained at 9MW with small variations using fuzzy based HESS (proposed method). Therefore the proposed method is maintaining the constant generator active power at any time with disturbances.

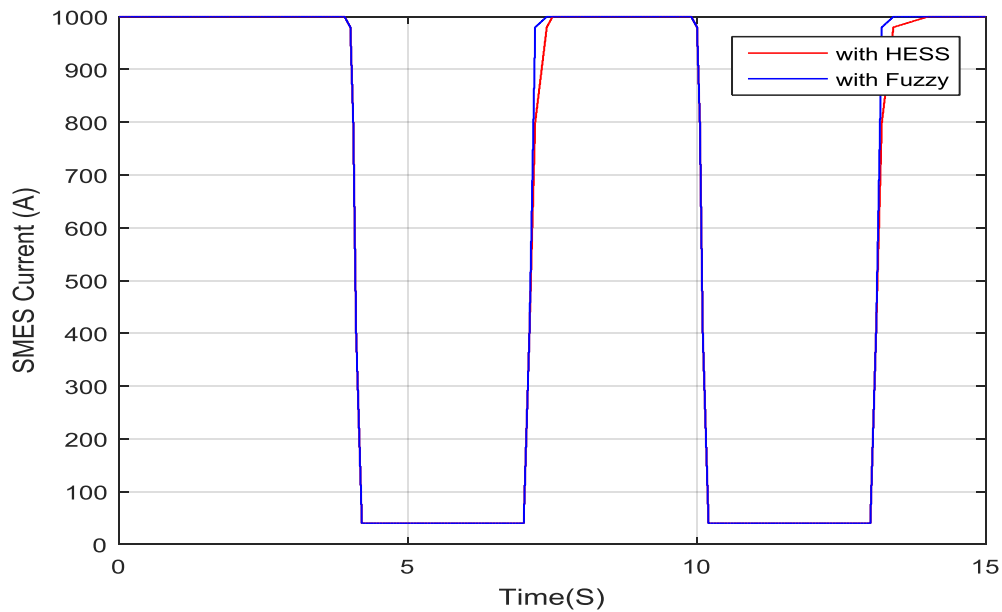


Fig. 13. SMES current with HESS and with proposed method.

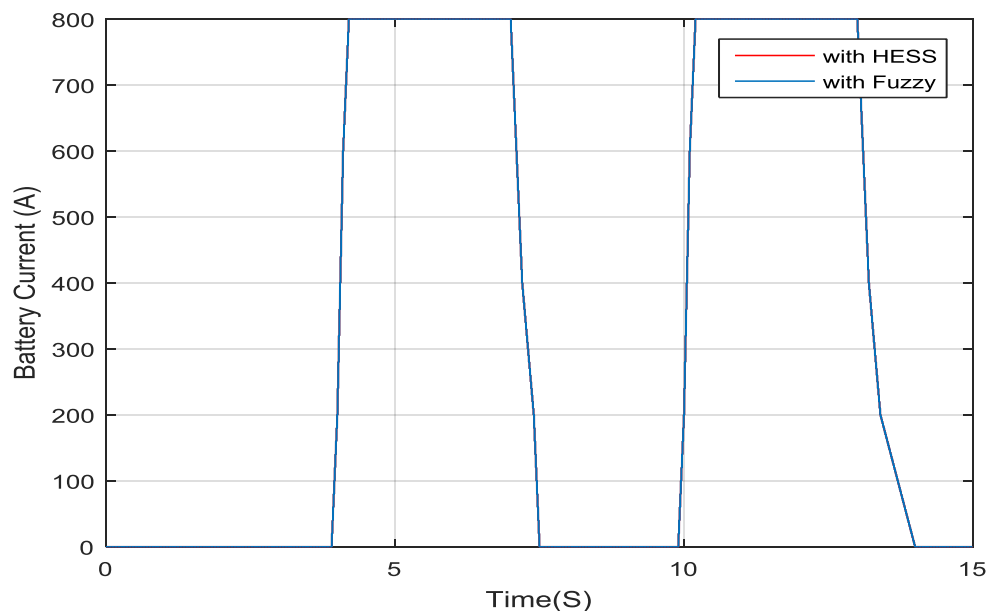


Fig. 14. Battery current with HESS and with proposed method.

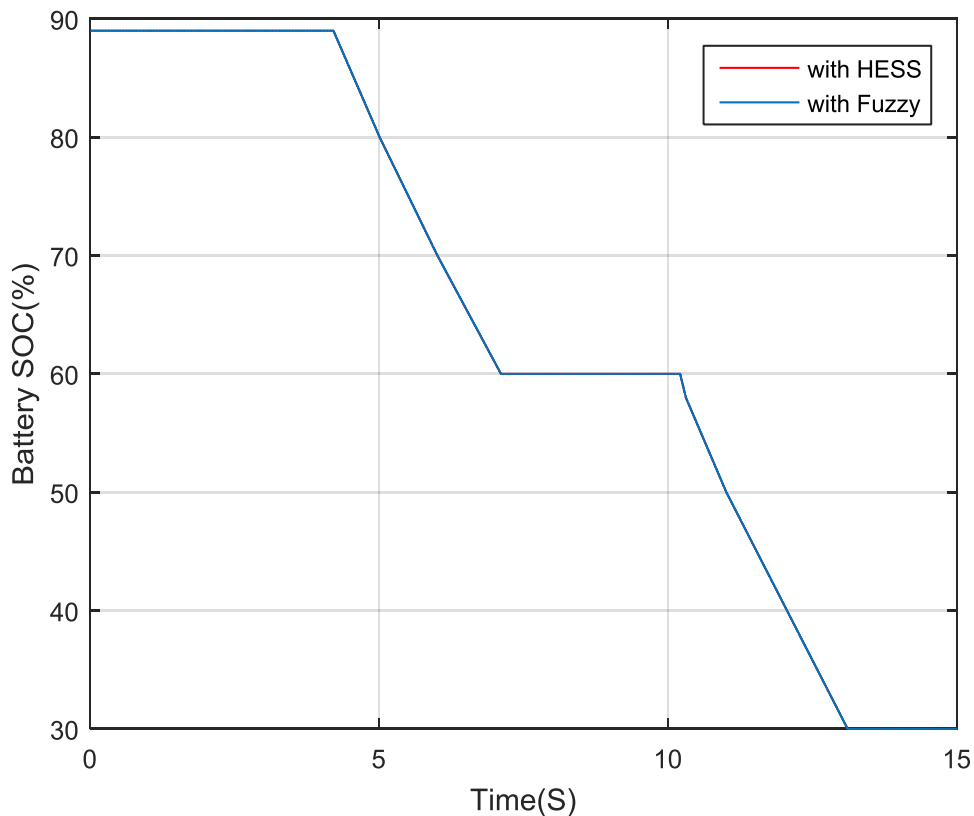


Fig. 15. Battery SOC with HESS and with proposed method.

Fig.13 and Fig.14 shows SMES and Battery currents with HESS and Fuzzy based HESS. Fig.15 shows the Battery SOC with HESS and Fuzzy based HESS.

V . CONCLUSIONS

This paper proposes Fuzzy based Hybrid Energy storage system for improving the stability of AES. In this method the Fuzzy controller is used to control the battery DC/DC controller output. The proposed method is tested on standard test system and results compared with three control strategies (without ESS, with ESS, with HESS), from the results it is concluded that the proposed method showed good performance during the pulse load periods. By supplying the pulse loads from the fuzzy based HESS, the system maintained the voltage at the targeted level, keeping the motor at the required speed and maintaining constant generation output power both with and without pulse loads.

REFERENCES:

- [1] Holmberg K, Andersson P, Erdemir A. Global energy consumption due to friction in passenger cars. *Tribology International* 2012;47:221e34.
- [2] Republic of Turkey. Ministry of Transport, Maritime and Communications. Turkish Transport and Communications Strategy, Target 2023.
- [3] Oak Ridge National Laboratory. Transportation energy data book: edition 33. Chapter 2: Energy. 2014.
- [4] Endresen Ø, Sørsgård E, Sundet JK, Dalsøren SB, Isaksen ISA, Berglen TF. Emission from international sea transportation and environmental impact. *Journal of Geophysical Research D* 2003;108:14e22.
- [5] Lee KJ, Shin D, Yoo DW, Choi HK, Kim HJ. Hybrid photovoltaic/diesel green ship operating in standalone and grid-connected mode e experimental investigation. *Energy* 2013;49:475e83.
- [6] M. Cupelli, *et al.* "Power Flow Control and Network Stability in an All-Electric Ship," in *Proceedings of the IEEE*, vol. 103, no. 12, pp. 2355-2380, Dec. 2015.
- [7] Monti, A., *et al.*, "Energy storage management as key issue in control of power systems in future all electric ships." *Power Electronics, Electrical Drives, Automation and Motion, 2008. SPEEDAM 2008. International Symposium on.* IEEE, 2008..

- [8] Vu, Tuyen V., *et al.* "Predictive control for energy management in ship power systems ...". *IEEE Transactions on Energy Conversion* (2017).
- [9] J. Lopez, "Combustion engine vs gas turbine—Ramp rate," Nov. 2016.[Online]. Available: Wartsila.com
- [10] N. H. Doerry and J. V. Amy, "The Road to MVDC," in *Proc. Intelligent Ships Symposium*, 2015.
- [11] J. F. Hansen and F. Wendt, "History and State of the Art in Commercial Electric Ship Propulsion, Integrated Power Systems, and Future Trends," in *Proceedings of the IEEE*, vol. 103, no. 12, pp. 2229-2242, Dec. 2015.
- [12] IEEE Recommended Practice for 1 kV to 35 kV Medium-Voltage DC Power Systems on Ships," in *IEEE Std 1709-2010*, vol., no., pp.1-54, Nov. 2 2010
- [13] T. Ise, M. Kita, and A. Taguchi, "A hybrid energy storage with a SMES and secondary battery," *IEEE Trans. Appl. Supercond.*, vol. 15, no. 2, pp. 1915–1918, Jun. 2005.
- [14] L. Trevisani, *et al.*, "Cryogenic fuel-cooled SMES for hybrid vehicle application," *IEEE Transactions on Applied Superconductivity*, 19(3), 2008-2011.
- [15] Cansiz, Ahmet, *et al.* "Integration of a SMES–Battery-Based Hybrid Energy Storage System into Microgrids." *Journal of Superconductivity and Novel Magnetism* (2017): 1-9.
- [16] Lashway, Christopher R., Ahmed T. Elsayed, and Osama A. Mohammed. "Hybrid energy storage management in ship power systems with multiple pulsed loads." *Electric Power Systems Research* 141 (2016): 50-62.
- [17] M. M. S. Khan, M. O. Faruque and A. Newaz, "Fuzzy Logic Based Energy Storage Management System for MVDC Power System of All Electric Ship," in *IEEE Transactions on Energy Conversion*, vol. 32, no. 2, pp. 798-809, June 2017.
- [18] S. Kulkarni and S. Santoso, "Impact of pulse loads on electric ship power system: With and without flywheel energy storage systems," *2009 IEEE Electric Ship Technologies Symposium*, Baltimore, MD, 2009, pp. 568-573.
- [19] Mahlia, T. M. I., *et al.* "A review of available methods and development on energy storage; technology update." *Renewable and Sustainable Energy Reviews* 33 (2014): 532-545.
- [20] Li, Jianwei, *et al.* "Design/test of a hybrid energy storage system for primary frequency control using a dynamic droop method in an isolated microgrid power system." *Applied Energy* 201 (2017): 257-269.
- [21] Ibrahim, Hussein, Adrian Ilinca, and Jean Perron. "Energy storage systems—characteristics and comparisons." *Renewable and sustainable energy reviews* 12.5 (2008): 1221-1250.
- [22] H. M. Chin, C. L. Su and C. H. Liao, "Estimating Power Pump Loads and Sizing Generators for Ship," in *IEEE Transactions on Industry Applications*, vol. 52, no. 6, pp. 4619-4627, Nov.-Dec. 2016.
- [23] J. Zhang, Q. Li, W. Cong and L. Zhang, "Restraining integrated electric propulsion system power fluctuation using hybrid energy storage systems", *IEEE conference on mechatronics and Automation*, Beijing, 2015, pp 336-340.
- [24] Hadjipaschalis, Ioannis, Andreas Poullikkas, and Venizelos Efthimiou. "Overview of current and future energy storage technologies." *Renewable and sustainable energy reviews* 13.6 (2009): 1513-1522.
- [25] Pickard, William F., Amy Q. Shen, and Nicholas J. Hansing. "Parking the power: Strategies and physical limitations for bulk energy storage in supply–demand matching on a grid whose input power is provided.. "Renewables and Sustainable Energy Reviews (2009)"; 1934-1945
- [26] Li, Jianwei, *et al.* "Design and test of a new droop control algorithm for a SMES/battery hybrid energy storage system." *Energy* 118 (2017): 1110-1122.
- [27] Farhadi, Mustafa, and Osama Mohammed. "Energy storage technologies for high-power applications." *IEEE Transactions on Industry Applications* 52.3 (2016): 1953-1961.
- [28] Shim, Jae Woong, *et al.* "Synergistic control of SMES and battery energy storage for enabling dispatchability of renewable energy sources." *IEEE Transactions on applied superconductivity* 23.3 (2013): 5701205-5701205.
- [29] Li, Jianwei, *et al.* "Analysis of a new design of the hybrid energy storage system used in the residential m-CHP systems." *Applied Energy* 187 (2017): 169-179.
- [30] Nie, Z., Xiao, X., Hiralal, *et al.* "Designing and Testing Composite Energy Storage Systems for Regulating the Outputs of Linear Wave Energy Converters." *Energies*, 10(1) (2017), p.114.
- [31] Hussein, M., Senjyu, , *et al.* "Control of a Stand-Alone Variable Speed Wind Energy Supply System. " *Applied Sciences*, 3(2) (2013)., pp.437-456.