

# **Analysis and Simulation of Adaptive Power System with Fuzzy Control for Managing Dynamic Loads**

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**ABSTRACT:** This paper proposes an Adaptive Power System with fuzzy logic controller, it is used to mitigate the negative impacts present on the ship platforms resulting from large dynamic loads. The Navy's future and near-term high-energy sensors and energy weapons will consume a large portion of the resources of the intended ship platform. These new systems will have extreme dynamic power profiles, including both periodic and aperiodic characteristics. These dynamics can cause sudden changes in power at the prime power system that can be stressing to platform systems, both to the generators and prime movers. By using the fuzzy controller for a nonlinear system allows for a reduction of uncertain effects in the system control and improve the efficiency. The APS has used to maintain generator/prime-mover reliability, and also it is used to improve sensor/weapon performance or improve metrics such as system weight, cooling demands, and ship fueling costs. By using the simulation results we can analyze the proposed method.

**KEYWORDS:** AC/DC converter, DC/DC converter, Adaptive power system (APS), fuzzy logic controller (FLC), Dynamic load profile.

## **I. INTRODUCTION**

The Adaptive Power System (APS) concept presented in this paper can be an enabling technology for sensors or weapons with large dynamic loads. If the dynamic profiles propagate back to the ship's electric plant, significant power-quality issues and generator/distribution losses can occur [1], [2]. In addition, the dynamic pulse loading may cause wear and tear on the gensets' mechanical parts [3]–[5]. The APS consists of energy storage, a bidirectional current source, and innovative control techniques. These innovative control techniques increase the energy storage utilization, thus minimizing the energy storage size. A block diagram of a conventional shipboard power system is shown in the Figure 1. Conventional systems have focused heavily on providing well-regulated voltages and clean power to the corresponding load. If the voltage dynamics seen at the load are to be minimized, the output impedance of each converter stage is minimized by using small series inductance values, large shunt capacitance values, and control loops with high bandwidths.

When compared with the passive filter method (brute-force method) the APS can support the pulsed load at a fraction of the size and weight needed. Using the active load method without excessive power dissipation as would exist (throw-away method), and for some specific applications without timeline restrictions as would be needed if using a refresh or recharging type system (restricted-timeline method).

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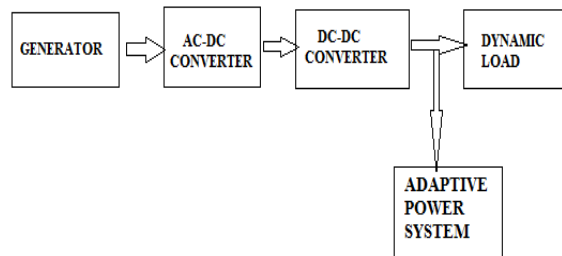


Fig. 1. A block diagram of a notional power system with the APS attached

The time limit for the enhanced operation is limited by the APS size, the size of the energy storage needed to provide the delta power, and the maximum average power allowed. This maximum allowed average power determines the corresponding duty cycle of this enhanced operation and hence the quickest allowed recharge time of the APS energy storage.

Consequently, a new approach is needed to manage the load dynamics of emerging Navy systems, The Adaptive Power System (APS) specifically addresses this need. The APS can be used to efficiently mitigate bus disturbances and reduce stress to the shipboard gensets by converting the dynamic power load seen by the shipboard power system into an equivalent rolling time average – essentially serving as an active low pass filter to the load dynamics. As shown in Figure 1, the APS can be added to an existing system. The APS consists of energy storage, a passive power filter, a bi-directional current source, and innovative control loops, as shown in Figure 2.

The bi-directional current source efficiently delivers the pulsed power demand from the APS energy storage to the desired sensor or weapon system, thus providing a buffer to the upstream power equipment.

The APS is similar to the active filter concept whereby the active filter provides the current needed to maintain the quality of the load current required by the upstream power system. Active filters have been used for years in alternating current (AC) power systems to reduce the current harmonics and improve the power factor presented to the source when the loads are nonlinear and electrically noisy [6]–[8].

In addition, active filters have recently become popular in direct current (dc) systems to reduce conducted emissions caused by the pulse-width modulation (PWM) switching action of the dc/dc converter load [9]. With the proper use of control loops and energy storage, the APS can reduce the rate at which the power demand on the generator changes, thus limiting the dynamics and spectral content seen by the generator - transforming a weapon or sensor system that had otherwise been incompatible with the platform's power system into one that is now feasible.

## II. ADAPTIVE POWER SYSTEM (APS)

### A. Overview

The goal of the APS is to minimize bus disturbances and stress to prime-power equipment by converting the dynamic power load into an equivalent rolling average of the power demand. The APS is designed to meet the proposed requirement as shown in Figure 3.

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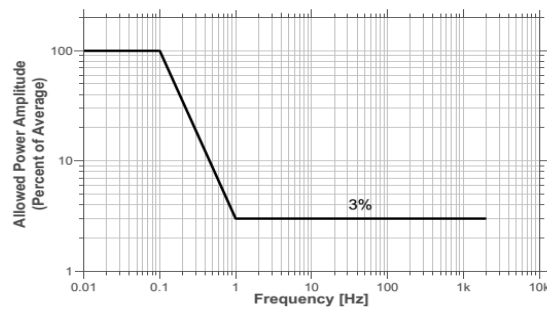


Fig. 3. The power ripple filtering requirement of the APS

The APS implementation must also not interfere with maintaining a stiff voltage (tightly regulated voltage) to the load. The top-level components of the APS include the energy storage capacitance and two control loops. One loop controls the APS output current to provide the required dynamic current to the load using the energy from the storage capacitance, and the other loop maintains the voltage across the energy storage capacitance to within the allowed rating.

Figure 2 provides the detail voltage and current waveforms for the APS as well as the generator power waveform during the application of a dynamic load profile.

### Operation of the Adaptive Power System is as follows:

- The current provided from the upstream power system is regulated by the APS to be equal to the filtered (0.13 Hz) current profile of the load demand. The compensation block regulates  $I_{bus}$  to be equal to  $I_{ref}$  by controlling the output current of the bi-directional current source (BDCS); see the bus-current and BDCS-current waveforms in Figure 2. The BDCS is a DC/DC converter that can process power in both directions – it can both absorb and deliver power.
- Hence, the AC component or dynamics of the load profile is not part of  $I_{bus}$  but is provided by the energy-storage capacitance via the BDCS.
- The energy-storage capacitance value is selected to be large enough to provide the source and sink currents to support the pulsed load demand. The value for the energy-storage capacitance is minimized by allowing the voltage across  $C_{store}$  to vary significantly, where  $U_{delivered} = 1/2 C_{store}(V_{t20} - V_{t2+})$ , minimizing the energy storage capacitance required.
- This provides significant weight and size savings compared to using an in-line high-powered low-pass filter (brute-force method).

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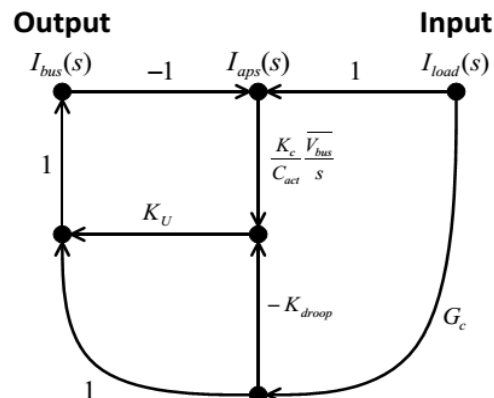


Fig. 4. Signal flow graph of APS for low frequency energy loop design where  $I_{bus} = I_{ref}$  and  $I_{load} = I_{load}$ .

- The voltage variation across Cstore is also decoupled from the load, allowing tight regulation of the bus voltage seen by the load to be maintained. Udelivered is the energy delivered or absorbed by the storage capacitance, and  $V_{t0}$  and  $V_{t+}$  are the corresponding voltages across the energy-storage capacitance just prior to the load disturbance and after the energy-storage capacitance has delivered or absorbed the desired energy

## B.APS Requirements for Notional System

To demonstrate the APS functionality and performance, a top-level design and simulation for a notional 300-kW system was performed. For this specific system the APS interfaces with the 375-VDC bus, as shown in Figure 1. The system was designed to support the following load and input–output performance specifications:

- Duty Cycle of Load: 0 to continuous
- Average Load Power: 0 to 300 kW
- Peak Load Power: 0 to 300 kW
- Input Voltage: 4160 VAC per MIL-STD-1399-680
- Input Interface Power Ripple Requirements: Figure 3
- Voltage Transients at the 375-V Bus Load Interface: maintain to better than  $\pm 5\%$

## C.APS Design Details for Notional System

### Control Loop Bandwidth Considerations:

Figure 5 provides the schematic details for the APS. The bi-directional current source is a modular design consisting of thirty-eight 8-kW modules.

The sizing and performance for the BDCS is based on the bi-directional buck topology [10], using a 100-kHz switching frequency and average current-mode control. The switching frequency is chosen high enough to obtain the needed control loop bandwidths (which will give the desired APS filtering performance) but low enough to maintain acceptable switching losses. The inner current loop bandwidth of the bi-directional current source is set to be between 15 and 25 kHz (varies with the voltage across Cstore), allowing the outer current loop of the APS to be set at 4 kHz.

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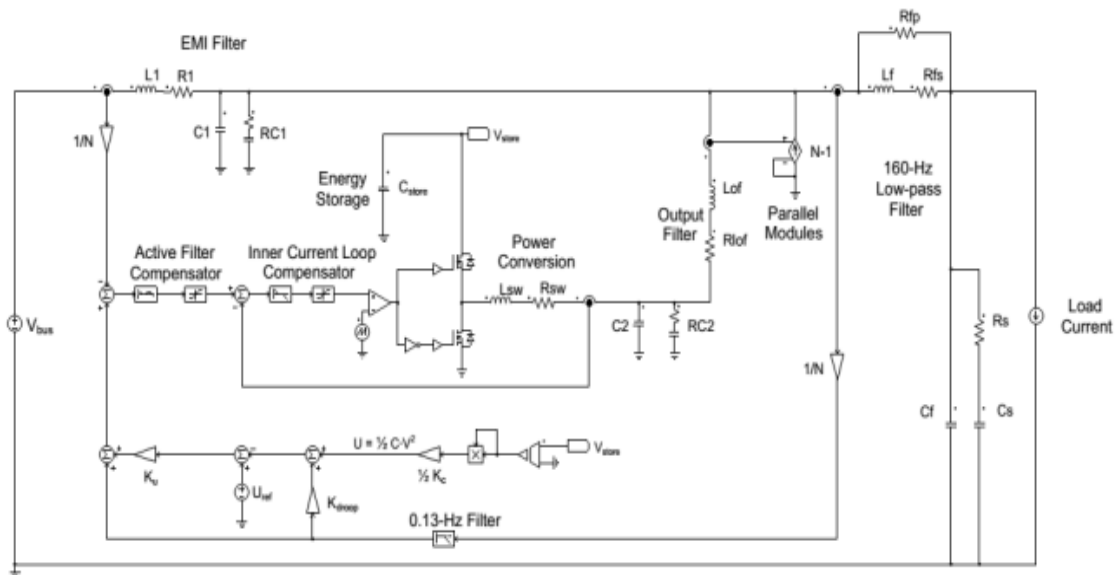


Fig. 5. The high-level schematic of an APS system used for simulation, where N is the total number of parallel modules (N=)38

To simplify the analysis, the preceding assumptions have been used, and therefore this signal flow graph is only valid for low frequencies. In Figure 4,  $I_{bus}$  is the controlled upstream bus current coming from the 375-V converter,  $I_{load}$  is the current to the load before the 160-Hz filter, and  $G_c$  is the transfer function of the 0.13-Hz filter, which has been selected to be a second order filter defined as

$$G_c = \frac{\omega_c^2}{s^2 + (2\zeta\omega_c)s + \omega_c^2} \quad (1)$$

where  $\omega_c$  is the corner frequency (in rad/s) and  $\zeta$  is the damping ratio. In this example,  $\zeta$  is equal to 0.9.

In addition,  $K_u$  is the energy-loop gain that determines the energy outer loop bandwidth,  $K_{droop}$  is the gain of the energy droop compensation (in J/A),  $C_{act}$  is the actual capacitance of  $C_{store}$  (in Farads), and  $K_c$  is the capacitance value (in Farads) used in converting the measured capacitor bank voltage,  $V_{store}$ , to energy, the transfer function  $\frac{I_{bus}(s)}{I_{load}(s)}$  can be determined as follows:

$$\frac{I_{bus}(s)}{I_{load}(s)} = \sum_{k=1}^N \frac{P_k \Delta_k}{\Delta} \quad (2)$$

where N is the total number of forward paths,  $P_k$  is the gain of the kth forward path,  $\Delta$  is the determinant, and  $\Delta_k$  is the cofactor of path k. The gain of forward paths are defined as

$$P_1 = G_c, \quad (3)$$

$$P_2 = -k_{droop} K_u G_c, \quad (4)$$

$$P_3 = k_u \frac{k_c \overline{V_{bus}}}{c_{act} s}, \quad (5)$$

where the bar over  $V_{bus}$  indicates a constant average value. There is only one loop in Figure 4, which is defined as

$$L = -k_u \frac{k_c \overline{V_{bus}}}{c_{act} s}, \quad (6)$$

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**TABLE I**  
**SIZE ANDWEIGHT OF THEAPS SYSTEM**

Component	Value	Size (ft <sup>3</sup> )	Weight (lbs.)
<b>Module</b>			
L <sub>of</sub> + R <sub>lof</sub>	10 μH + 1 mΩ	0.001	0.15
C <sub>2</sub> *	3.3 μF	--	--
RC <sub>2</sub> branch*	0.91 Ω + 68 μF	--	--
L <sub>sw</sub> + R <sub>sw</sub>	0.1 mH + 6 mΩ	0.004	1.4
C <sub>store</sub>	86.7 mF	2.1	169.2
Heat Sinks	-	0.1	4
Miscellaneous	-	0.1	10
<b>Total Modules</b>			38
<b>EMI Filter</b>			
L <sub>1</sub> + R <sub>1</sub>	25 μH + 0.3 mΩ	0.12	49
C <sub>1</sub>	94 μF	0.01	1
RC <sub>1</sub> branch	0.31 Ω + 1.9 mF	0.03	5
<b>Low-Pass Filter</b>			
L <sub>f</sub> + R <sub>fs</sub>	25 μH + 0.3 mΩ	0.12	49
C <sub>f</sub>	40 mF	0.13	21.9
C <sub>s</sub> + R <sub>s</sub>	0.2 F + 25 mΩ	1.25	217.7
R <sub>fp</sub> *	33 mΩ	--	--
<b>Grand Total</b>		93.0	7364

The determinant is then

$$\Delta = 1 - L = 1 + k_u \frac{k_c \sqrt{V_{bus}}}{c_{act} s} \quad (7)$$

Because the loop, L, touches all the forward paths, the cofactor for each forward path is simplify defined by

$$\Delta_1 = \Delta_2 = \Delta_3 = 1 \quad (8)$$

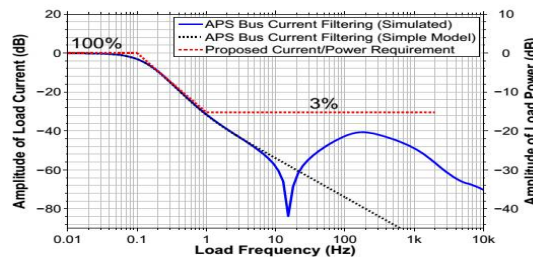


Fig. 6. The bus current filtering performance of the APS with the proposed requirement overlaid (for example, a 100 kW average load is allowed 3 kW peak ripple at 1 Hz). Because the bus voltage is approximately constant, current filtering directly relates to power filtering.

Figure 6 demonstrates that this equation's predictions (black dashed line) are nearly identical to the detailed simulation results (solid blue line) up to 4 Hz, at which point interactions with the current control-loop compensator begins to appear. Figure 6 provides the time-constant requirement via the frequency-domain specification needed to determine the storage-capacitance nominal value, C<sub>design</sub>.

This results since K droop's units are Joules/Ampere. Knowing the amount of energy used,

$$U_{total} = I_{loadmax} K_{droop} \quad (9)$$

$$U_{max} = \frac{1}{2} C_{design} (V_{max}^2 - V_{min}^2) \quad (10)$$

along with the maximum available energy for use the corresponding capacitance value can be solved for

$$C_{design} = \frac{2I_{loadmax} K_{droop}}{(V_{max}^2 - V_{min}^2)} \quad (11)$$

Here, I<sub>loadmax</sub> is the designed maximum load current of the module, V<sub>max</sub> is the maximum allowed capacitor voltage, V<sub>min</sub> is the minimum allowed capacitor voltage.

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Table II provides a summary of predicted component losses. The MOSFETs used in the implementation of the BDCS are silicon carbide devices. Silicon carbide devices are selected because of the inherently low drain to source parasitic capacitance, which is crucial to minimizing the switching losses when operating at the high voltage levels with hard switching.

TABLE II  
POWERLOSSES OF THEAPS SYSTEM

<b>Single Module Losses</b>	
Max FET (two Cree SiC FETs)	91.9 W
Switching Inductor	32.0 W
Output Filter Inductor	0.5 W
C <sub>store</sub> Leakage and Balance Resistors	2.6 W
Total Module Losses	127.0 W
Number of Modules	38
Total BDCS Converter Losses	4826 W
<b>Other Losses</b>	
EMI or Low Pass Filter	210 W
Low Pass Filter Damping	2 W
Miscellaneous & Margin	1512 W
<b>Total System Losses</b>	<b>6550 W</b>

### III. PROPOSED REQUIREMENTS

The Navy's MIL-STD-1399-680 addresses pulse loading requirements, but only deals with pulses that occur infrequently – less than once every 45 seconds [11]. A requirement is needed that protects the genset and distribution bus against the dynamics resulting from frequent and repetitive pulsing loads but which is not as restrictive as the present requirement of only allowing a single pulse once every 45 seconds. Meeting the following requirement would provide this protection, and with the use of the APS, this requirement is feasible to implement, even for systems with large dynamic power profiles.

#### Proposed Pulsed Load Requirement:

The combined three-phase peak power ripple as seen by the shipboard generator(s) at any single frequency generated by the load shall be less than the limits defined by Figure 3. The resulting allowed load profile proposed in Figure 3 has been matched to the generator and prime mover performance. Typical gensets' response times to a significant load change are on the order of 1.0 to 1.5 sec [12], [13]. If the rise and fall times for power changes (ramp rate) seen by the generator are controlled to be slower than the genset's response times, the generator and prime-mover control loops will be able to maintain the voltage and speed regulation, bus disturbances will be kept to a minimum for such a slow-changing power profile, and sub-synchronous resonances will not be excited because the disturbances are at lower frequencies.

#### FUZZY LOGIC CONTROLLER

In FLC, basic control action is determined by a set of linguistic rules. These rules are determined by the system. Since the numerical variables are converted into linguistic variables, mathematical modeling of the system is not required in FC.



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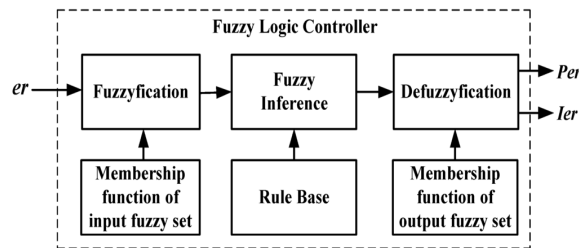


Fig.7.Fuzzy logic controller

The FLC comprises of three parts: fuzzification, interference engine and defuzzification. The FC is characterized as i. seven fuzzy sets for each input and output. ii. Triangular membership functions for simplicity. iii. Fuzzification using continuous universe of discourse. iv. Implication using Mamdani's, 'min' operator. v. Defuzzification using the height method.

TABLE III: Fuzzy Rules

Change in Error	Error						
	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PB	PM	PM	PS	Z
NM	PB	PB	PM	PM	PS	Z	Z
NS	PB	PM	PS	PS	Z	NM	NB
Z	PB	PM	PS	Z	NS	NM	NB
PS	PM	PS	Z	NS	NM	NB	NB
PM	PS	Z	NS	NM	NM	NB	NB
PB	Z	NS	NM	NM	NB	NB	NB

### Fuzzification:

Membership function values are assigned to the linguistic variables, using seven fuzzy subsets: NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium), and PB (Positive Big). The Partition of fuzzy subsets and the shape of membership CE(k) E(k) function adapt the shape up to appropriate system. The value of input error and change in error are normalized by an input scaling factor. In this system the input scaling factor has been designed such that input values are between -1 and +1. The triangular shape of the membership function of this arrangement presumes that for any particular E(k) input there is only one dominant fuzzy subset. The input error for the FLC is given as

$$E(k) = \frac{P_{ph(k)} - P_{ph(k-1)}}{V_{ph(k)} - V_{ph(k-1)}} \quad (12)$$

$$CE(k) = E(k) - E(k-1) \quad (13)$$

### Inference Method:

Several composition methods such as Max-Min and Max-Dot have been proposed in the literature. In this paper Min method is used. The output membership function of each rule is given by the minimum operator and maximum operator. Table 1 shows rule base of the FLC.



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## Defuzzification:

As a plant usually requires a non-fuzzy value of control, a defuzzification stage is needed. To compute the output of the FLC, „height“ method is used and the FLC output modifies the control output. Further, the output of FLC controls the switch in the inverter. In UPQC, the active power, reactive power, terminal voltage of the line and capacitor voltage are required to be maintained. In order to control these parameters, they are sensed and compared with the reference values. To achieve this, the membership functions of FC are: error, change in error and output. The set of FC rules are derived from

$$u = -[\alpha E + (1-\alpha)*C] \quad (14)$$

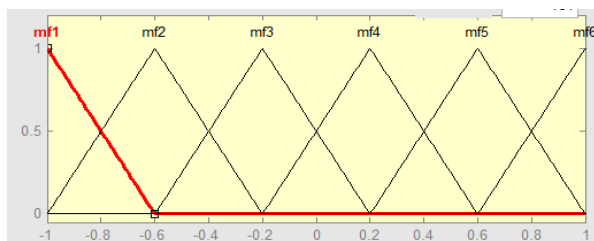


Fig 8 input error as membership functions

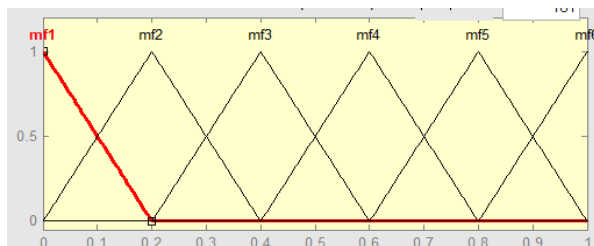


Fig 9 change as error membership functions

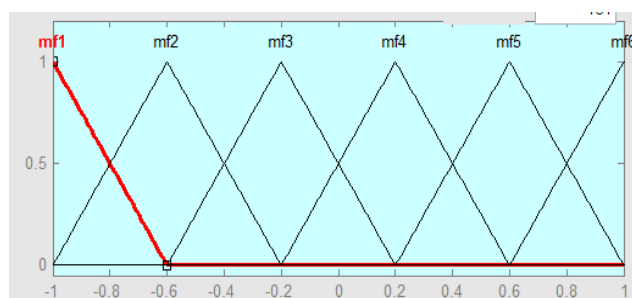


Fig.10 output variable Membership functions

Where  $\alpha$  is self-adjustable factor which can regulate the whole operation. E is the error of the system, C is the change in error and u is the control variable.

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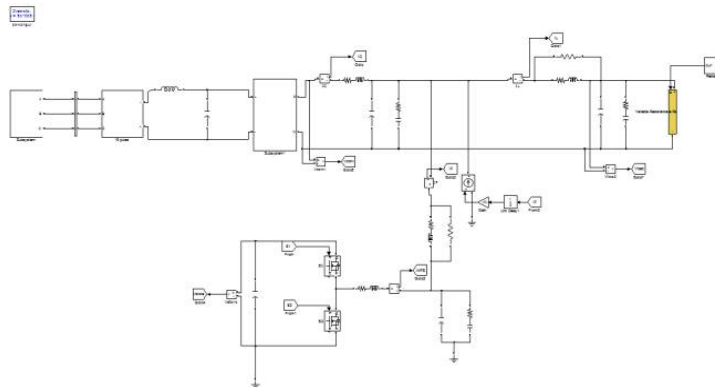


Fig11. Block diagram of simulation

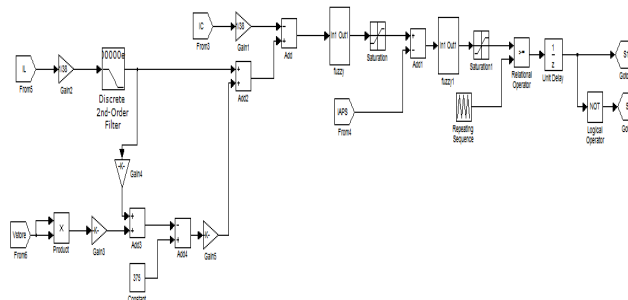


Fig 12. Control block diagram of simulation

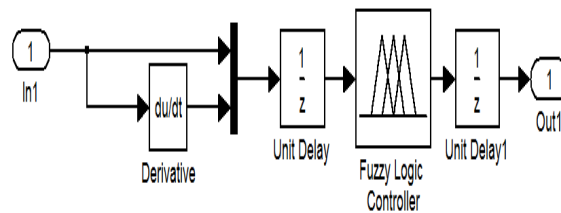


Fig13. Block diagram of fuzzy logic controller

## B.Simulation results for Notional System

To demonstrate the effectiveness and benefits of the APS, Figures 14(a) and 14(b) provide simulation results for various waveforms in the system when a dynamic load is applied both with and without use of the APS.

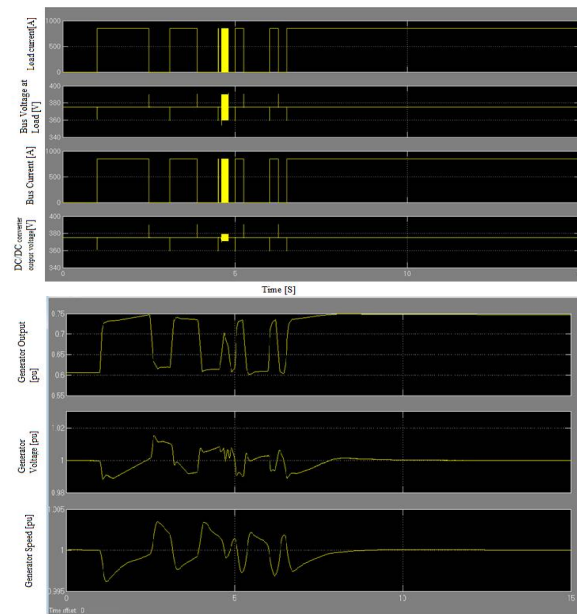
The load profile chosen in Figures 14(a) and 14(b) not only contains varying duty cycles but also simulates the extreme stressing condition.

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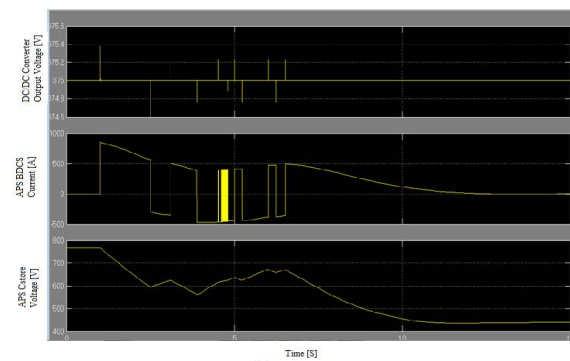
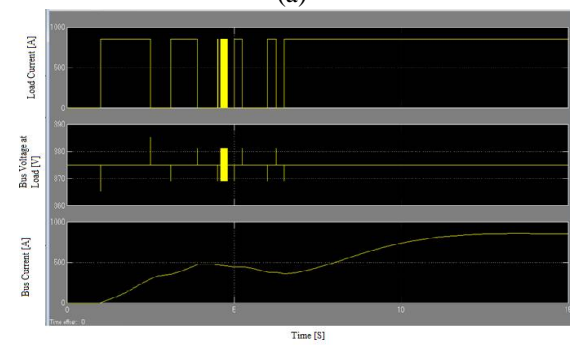
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(a)

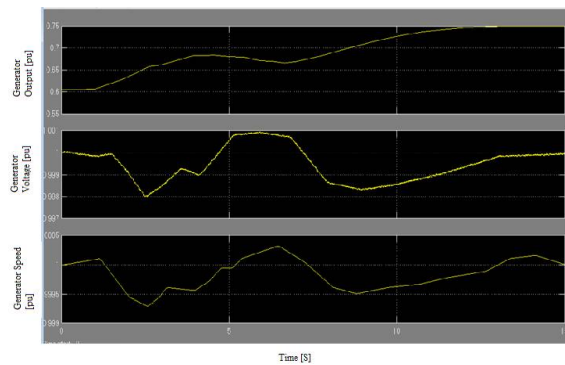


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(b)

Fig. 14. Simulation results of the first load profile at Load and Generator. (a) Without APS. (b) With APS.

Fig. 14(a) The results also demonstrate that the ac/dc and dc/dc converters do little to reduce the low to medium frequency content, with most of the dynamic load appearing at the generator terminals when the APS is not used.

Fig. 14(b) also shows the voltage waveform of the storage capacitor and the current waveform of the bi-directional current source, demonstrating the APS's capability of providing the dynamic demand of the load resulting in the generator only having to provide the rolling average of the load power profile.

The 375-V bus voltage delivered to the load is also shown in Fig. 14(b), indicating that the 5% transient regulation requirement is met. At time 6.5 s in Fig. 7(b), the load switches to a constant load and the APS consumes no power (APS output current goes to zero) after about 5 s from this point in time, demonstrating the efficient conditioning method provided by the APS.

## IV. CONCLUSION

In this paper the Adaptive Power System (APS) with fuzzy logic controller concept presented can be an enabling technology for sensors or weapons with large dynamic loads, which without the APS would be incompatible with the upstream shipboard generator and distribution bus. In FLC, basic control action is determined by a set of linguistic rules. These rules are determined by the system. The APS consists of energy storage, a bidirectional current source, and innovative control techniques. The APS has used to maintain generator/prime-mover reliability, and also it is used to improve sensor/weapon performance or improve metrics such as system weight, cooling demands, and ship fueling costs. By using the fuzzy controller for a nonlinear system allows for a reduction of uncertain effects in the system control and improve the efficiency. The APS design with fuzzy controller is presented along with simulation results verifying the concept. By using the simulation results we can analyze the proposed method.

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