Adaptive Power System for Controlling Dynamic Loads of an Induction Motor

D.Reshma Begum & B.Naga Lakshmi

[1]M Tech student of Dr Kvsrit, Kurnool, India.

[2]Assistant Professor, Department of Eee, Dr Kvsrit, Kurnool,India.

ABSTRACT

The Navy's future and close term high-vitality sensors also, vitality weapons will expend a substantial segment of the assets of the planned ship stage. A considerable lot of these new frameworks will have extraordinary dynamic power supplies, including both periodic and aperiodic qualities. These dynamic utilities can cause sudden changes in control at the prime power system that can focus to platform frameworks, both to the generators and prime movers and also other loads sharing the regular dissemination transport. This paper presents the utilization of new adaptive power framework (APS) to moderate the negative impacts required on induction motor variable speed because of extensive dynamic loads. A notional size of the equipment required to execute the APS configuration is introduced along with simulation results about confirming the concept.

Keywords— AC/DC converter, electromagnetic load torque, energy storage, ferrite, frequency modulation, generators, governor, harmonics, nano crystalline, power factor, power quality, prime movers, pulsed load, regulation, shipboard platform, silicon carbide, Simulink,.

I. INTRODUCTION

A block diagram of a conventional shipboard power system is shown in the dashed box of Figure 1.1 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. However, this type of system does little to prevent the mid to low frequency load dynamics from propagating back to the distribution bus and generator.

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]. Torsional stresses to the shaft of the ship's prime mover can result due to the very large and quickly changing electromagnetic load torques. These dynamic electromagnetic load torques may also excite the shaft's torsional resonances, typically referred to as sub-synchronous resonances [2], [6], adding additional stresses to the shaft.

Present-day methods that can be used to buffer the prime power system from dynamic loads include the following:
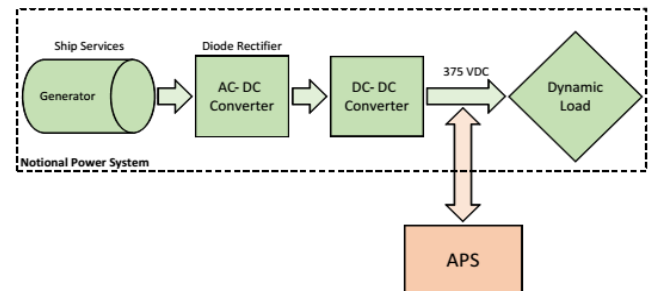
Figure.1.1 A block diagram of a notional power system with the APS attached

1. The "brute-force method", where by passive filters are used to smooth the dynamics of the load profile. Al though this method results in minimal additional power losses, achieving the smoothing or filtering needed by the shipboard power system requires filter sizes and weights that are impractical and prohibitive for ship installation.

2. The "throw-away-power method", whereby when the load is not using the maximum power allocated, the excess power is dissipated in an active load [7]. This type of system maintains a constant load profile to the generators, thus addressing the genset reliability and bus disturbance concerns. However, it can have severe impacts on system efficiency resulting

from the large additional power dissipation, increasing both cooling requirements and fueling costs for ship platforms.

3. The "restricted-timeline method", which requires a defined charging time for the system whereby the pulse power can only be supplied at predefined scheduled time intervals. For these systems, the successive launch times or fire times (repetition rate) and corresponding system performances are limited by the charging times of the system. Some examples of such systems are the Electromagnetic Aircraft Launch System (EMALS) and rail guns [8], [9].

Consequently, a new approach is needed to manage the load dynamics of emerging Navy systems – one that is not compromised by the disadvantages noted above for existing systems. The new 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.

Figure.1.2 An overview of the functionality of the APS system

As shown in Figure 1.2, 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 1.2. 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 can support the pulsed load at a fraction of the size and weight needed when compared with the passive filter method (brute-force method), without excessive power dissipation as would exist if using the active load method (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).

If for all of the desired combinations for duty cycle, repetition rate, and peak power levels, the average power over a load cycle is within the allotted generator power, the APS can be designed such that no timeline restrictions exist. This is the case for the example of the 300-kW system given in Section III. On the other hand, if there are profiles whereby the average power is above the generator capability, the APS can be used to provide the needed delta in power, allowing this enhanced operation of the sensor/weapon for short periods of time. 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.

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 [10]–[12]. 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 [13]. For an AC system the active filter produces a corresponding output current that when combined with the load current results in a clean sinusoidal current at the power system's fundamental frequency (e.g., 60 Hz). For a DC system the active filter operation is very similar to that for an AC system with the high frequency PWM switching noise of the load being canceled. Typical use of the active filter has focused on
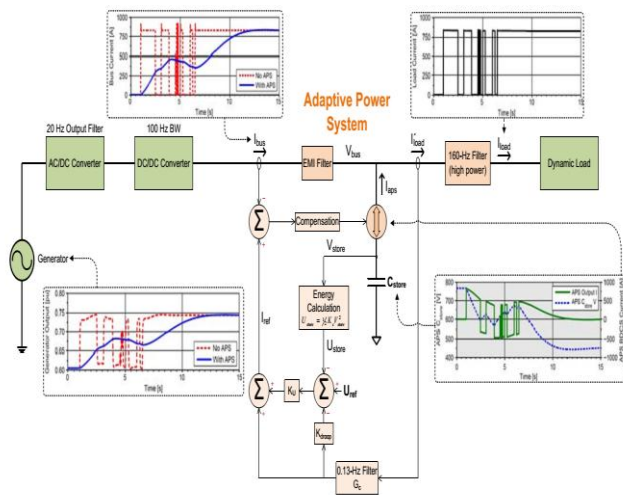
removing the harmonic currents (or for DC systems, the PWM switching currents and corresponding harmonics) riding on top of the average power draw. These noise current magnitudes are usually much less than the fundamental or DC current magnitude.

Conversely, for the new sensors and weapons it is not just a matter of removing a small level of noise riding on top of the average power draw. For these types of loads, the average power draw is not constant and may vary greatly. In addition, these dynamic loads not only produce noise at harmonic frequencies but also large levels of noise at inter harmonic (not multiples of 60 Hz) and sub-harmonic (less than 60 Hz) frequencies. 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)

Adaptive Power Systems (APS) was created in 2003 to manufacture and distribute a complete and extensive line of AC and DC power equipment to meet world-wide applications.

Adaptive Power System products are designed to fill the needs of power conversion for either AC or DC applications. Our AC to AC converters provide frequencies and voltages found around the world for both commercial and military avionics or shipboard applications. Each system includes features that customers have asked for over the years. For instance, each unit in the APS product range will accept multiple frequency and voltage inputs, offers fully adjustable output frequency and a very broad adjustable voltage range that permits the duplication of any utility power configurations. The APS range is available in sizes from 500 VA to 120 kVA.
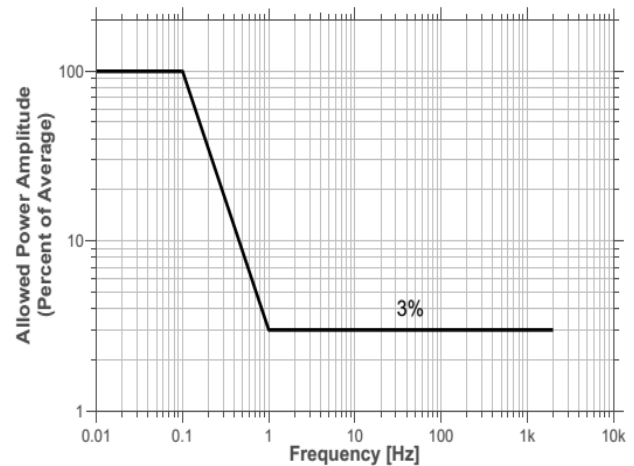
Figure.2.1 The power ripple filtering requirement of the APS

Operation of the Adaptive Power System is as follows:

a. 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 4.1. The BDCS is a DC/DC converter that can process power in both directions − it can both absorb and deliver power.

b. 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.

c. 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 $U_{delivered} = \frac{1}{2} C_{store}(Vt2_0 − Vt2_+)$, minimizing the energy storage capacitance required.

   I. This provides significant weight and size savings compared to using an in-line high-powered low- pass filter (brute-force method).

II. The voltage variation across C_{store} is also decoupled from the load, allowing tight regulation of the bus voltage seen by the load to be maintained. $U_{delivered}$ is the energy delivered or absorbed by the storage capacitance, and Vt0 and Vt+ 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.

d. The current reference, I_{ref}, is slowly adjusted to keep the voltage across C_{store} within the allowable boundaries. This is achieved by regulating the energy stored in C_{store} via a slow-moving outer loop. The block labeled Ku in Figure 4.2 sets the bandwidth of the outer energy loop while K droop is used to optimize the energy utilization of C_{store}.

Controlling the load dynamics is accomplished by properly selecting the corner frequency for the 0.13-Hz signal filter in the current feedback path to be lower than the genset's control loop bandwidths. The corner-frequency selection for the signal filter is the critical design parameter in the APS that controls the protection provided to the generator and prime mover; hence this filter sets the allowed power ramp rate and dynamics seen by the generator.
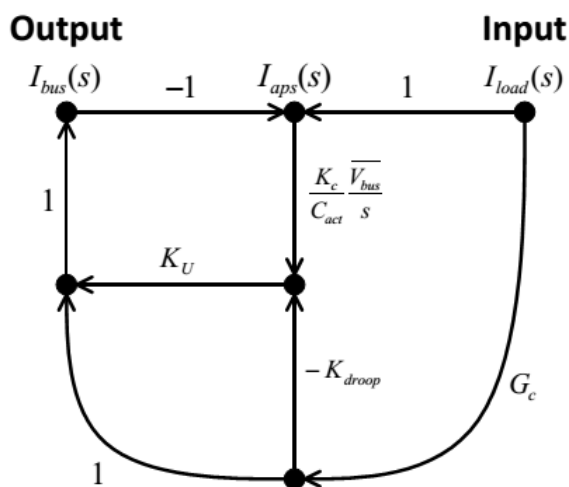
Figure.2.2 Signal flow graph of APS for low frequency energy loop design where
I_{bus} = I_{ref} and I_{load} = I_{load}

To limit the bandwidth requirement of the APS, a low-pass filter between the APS and the load is used. The low-pass filter reduces the response-time requirement on the APS by reducing the high-frequency components of the load pulses seen at the bus connection to the BDCS. The corner frequency for the low-pass filter is approximately 160 Hz. The APS can both sink and source current through the BDCS, which is implemented with an efficient high-frequency DC/DC converter. Because the pulsed power is no longer provided by the generator, the value of C_{store} must be selected large enough to provide the source and sink currents to support the pulsed load demand in the time consistent with the 0.13-Hz signal-filter time constant, while concurrently maintaining the voltage across C_{store} within its defined allowable range. The voltage range on C_{store} is indirectly controlled by regulating the energy stored in C_{store}. The current command, I ref, is slowly adjusted to maintain the proper energy storage, thus keeping the proper voltage range across C_{store}. Energy regulation is chosen over voltage regulation to linearize the outer loop transfer function with respect to the BDCS controlled output current. Energy regulation eliminates the outer loop dependency on the duty cycle of the BDCS. The duty cycle of the BDCS varies with the voltage across C_{store}. Because the transfer function $\frac{U_{delivered}(s)}{I_{aps}(s)}$ is independent of the voltage across C_{store}, as desired the outer bandwidth will remain constant as the voltage across C_{store} changes. If a voltage loop is used instead, the outer-loop bandwidth will vary with the DC operating point, potentially affecting performance.

To reduce the energy-storage capacitance needed, an adaptive reference for the energy-storage loop is used, whereby the reference is biased by the 0.13-Hz filtered load current. This technique is very similar to droop compensation regulation. If the 0.13-Hz filtered load current is at the maximum value, then the reference for the energy storage will be set to the minimum value, putting the capacitor in the optimal state for absorbing energy. If the 0.13-Hz filtered load current is at zero Amps, then the reference for the energy storage will be set to the maximum value, putting the capacitor in the optimal state for providing energy. This adaptive control maximizes the energy storage utilization by reducing the required capacitance by a factor of 2.

III. SIMULATION RESULTS

The generator model used in the simulation is based on Simulink's Synchronous Machine standard sixth-order electrical model and is rated for 2.28 MVA. The AVR (voltage) control loop is set at 0.6 Hz and the governor (speed) control loop is set at 1 Hz. The AC/DC converter is an 18-pulse diode rectifier model with an output filter corner frequency of approximately 20 Hz. The major models used to create the AC/DC converter are the three phase-shifting transformers and the 6-pulse diode rectifiers, both from Simulink's Sim Power Systems toolbox [21].

The DC/DC converter voltage control loop is set at 100 Hz. The DC/DC converter is modeled using the standard non-switching average model, which uses an ideal transformer for transforming DC and AC information with the transformer turns ratio controlled by the converter duty cycle [17]. This same technique is used to model the APS bi-directional current source. To demonstrate the effectiveness and benefits of the APS, Figures provide simulation results for various waveforms in the system when a dynamic load is applied both with and without use of the APS. For this simulation, the generator is biased with a 0.6 p.u. load prior to applying the dynamic load.

The load profile chosen not only contains varying duty cycles but also simulates the extreme stressing condition of having significant off times in the load profile, simulating a bang-ON–bang-OFF operation of the 300 kW load, the most stressing condition for the genset. Note that for this extreme profile, the ramp rate seen by the generator with the use of the APS is extremely slow, with the maximum ramp rate being less than 0.1 MVA/sec (where 1 p.u. (per unit) is equal to 2.28 MVA). The generator control loops can easily maintain regulation through this very slow changing disturbance. 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.
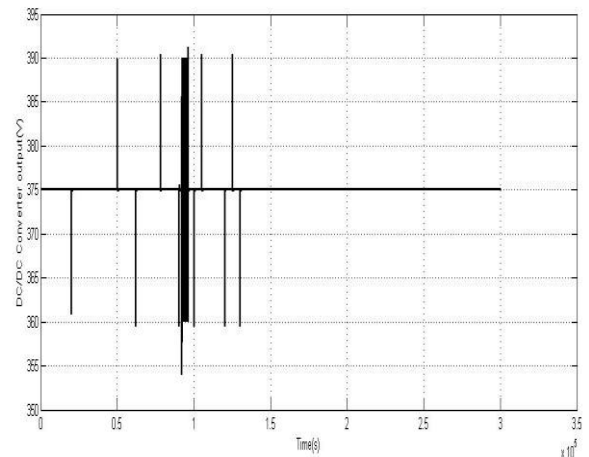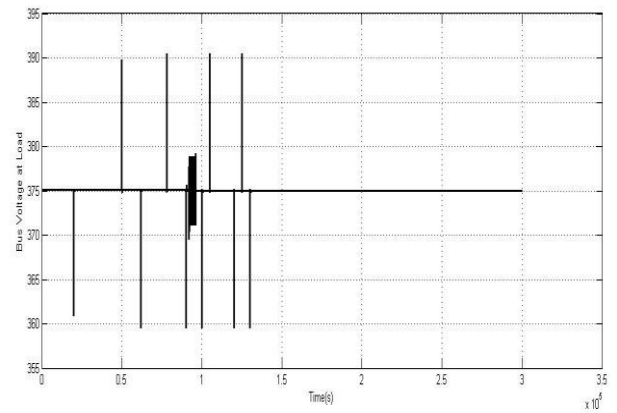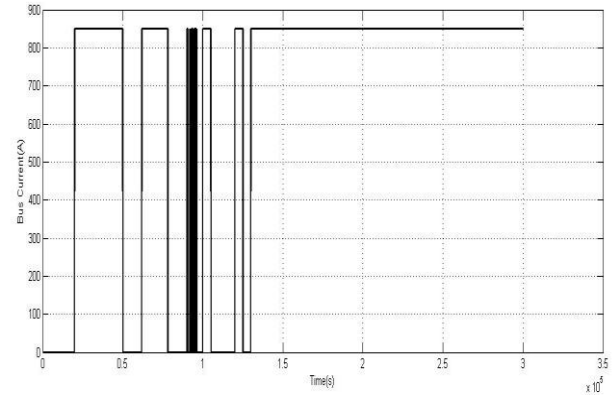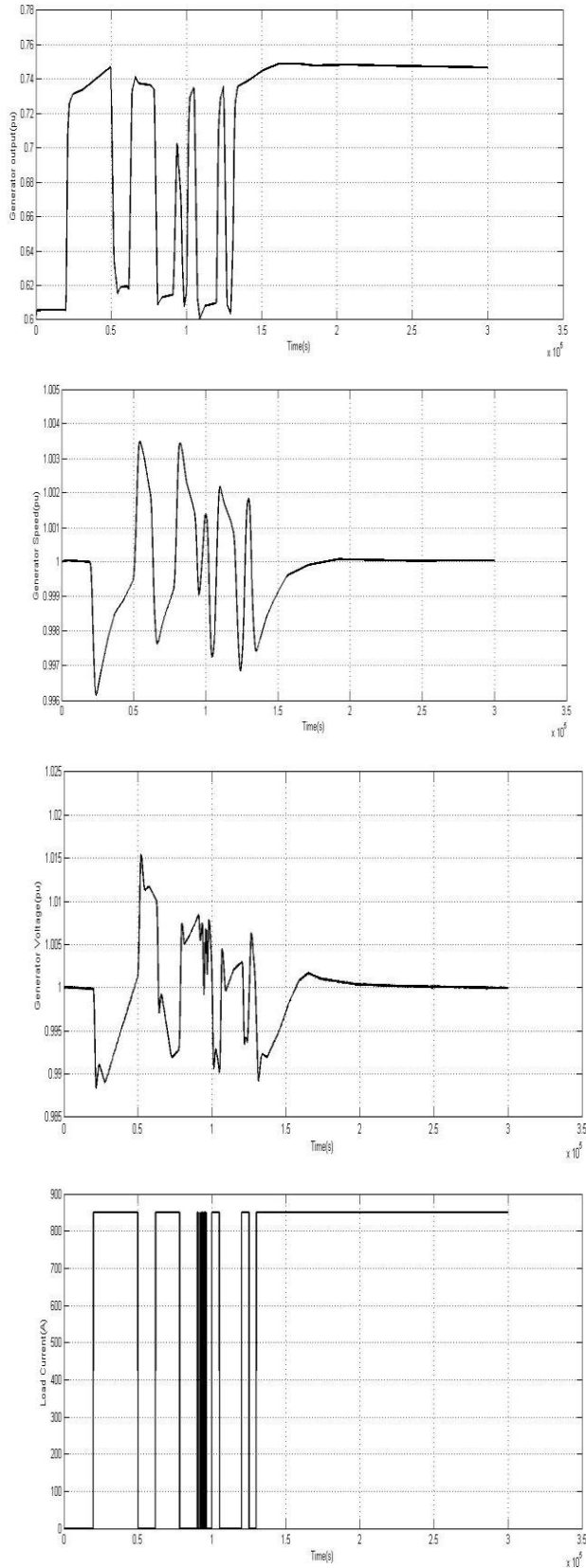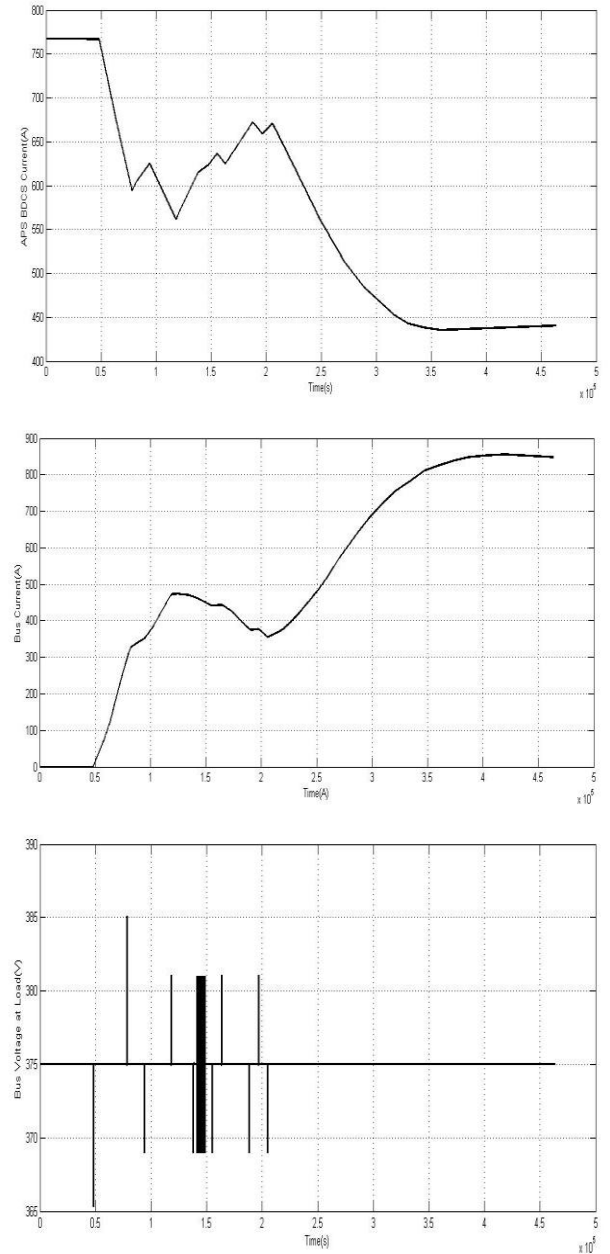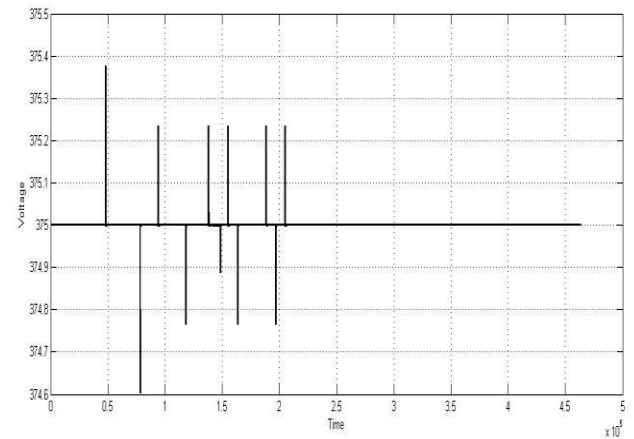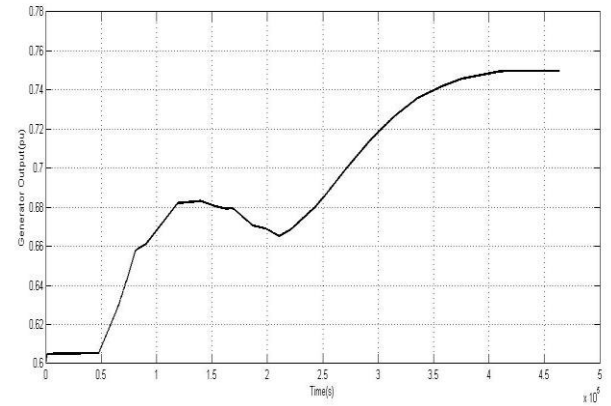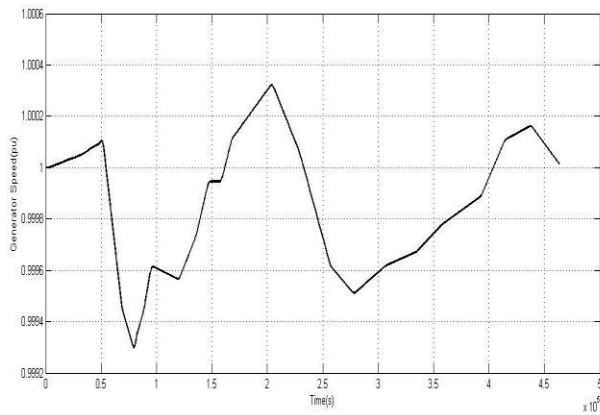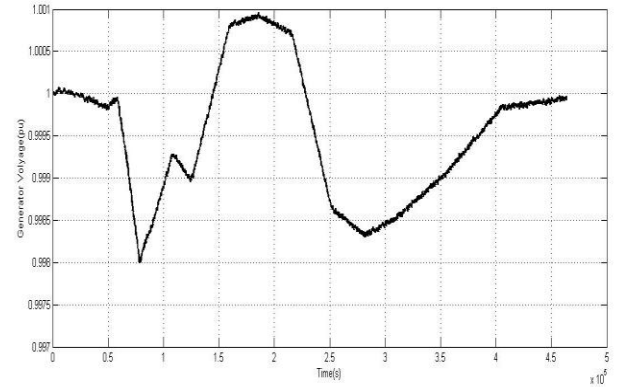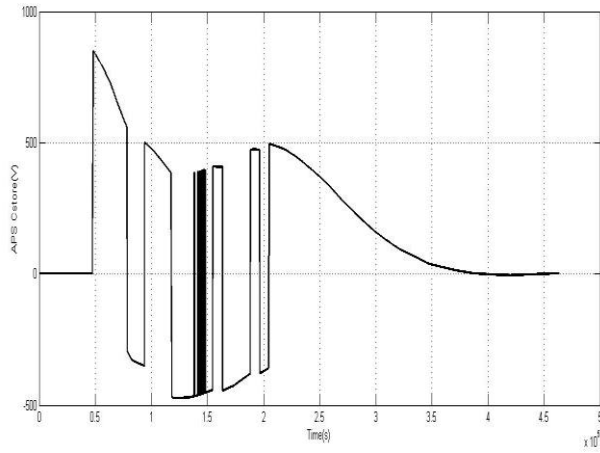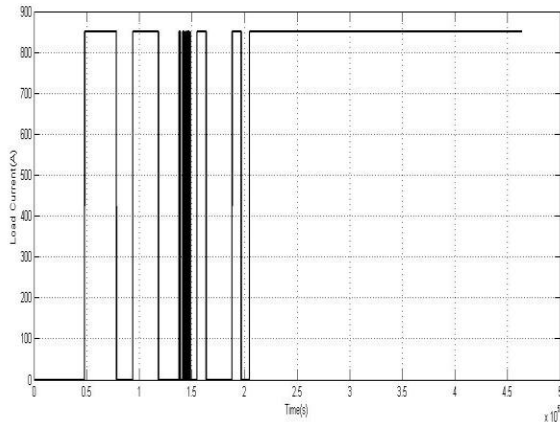
Figure.3.1 Waveforms without APS

Figure.3.2 Waveforms with APS

As expected, the generator's voltage and prime-mover's speed (frequency) disturbances are much smaller with the use of the APS. The frequency and voltage modulation created by the load without the APS demonstrates that a nominal system of this size encroaches on the respective modulation limits of 0.5% and 2% set by MIL-STD-1399-680 [14]. A larger load or this load combined with other ship loads could result in a noncompliant system.

The genset model used does not simulate mechanical behaviors of the generator, such as shaft or other mechanical resonances. However if shaft resonances are excited (e.g., sub synchronous resonances), significant torques larger than the full-load steady-state torque could be seen on the shaft [6]. Furthermore, if these disturbances exist, mechanical stresses to other parts of the genset can also occur. As is evident in the results, the APS significantly reduces frequencies that could excite potentially dangerous mechanical resonances as well as cause fatigue due to excessive movements.

Figures 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, indicating that the ±5% transient regulation requirement is met. At time 6.5 seconds in, the load switches to a constant load and the APS consumes no power (APS output current goes to zero) after about 5 seconds from this point in time, demonstrating the efficient conditioning method provided by the APS. If the APS is used for a periodic dynamic load application, the generator

will see essentially a constant load with only a benign very small power ripple riding on top of the load's average power draw.

Above figure demonstrates the filtering capability of the APS in the frequency domain. The solid blue line in this figure shows the load rejection provided by the APS as viewed from the output of the upstream 375-V converter. The proposed filtering requirement (dashed red line with the 100% and the 3% limits annotated) has been superimposed on the APS results, showing that the APS satisfies the requirement. As can be seen from Figure 3.2, the APS removes the low to mid frequencies that can degrade the generator shaft or could excite potentially hazardous resonances. In addition, removing these frequencies from the electric plant distribution bus means the bus quality for other users is improved – meaning fewer disturbances will exist due to the load dynamics interacting with the bus impedances and the generator.

Induction motor, which is used for wide area inductive applications like large dynamic loads such as the loads which consumes more amount of power for our consumer applications, in this mode of operation the adaptive power system controls load, which is applied on the rotor side of an induction motor, and can control the speed of induction motor.
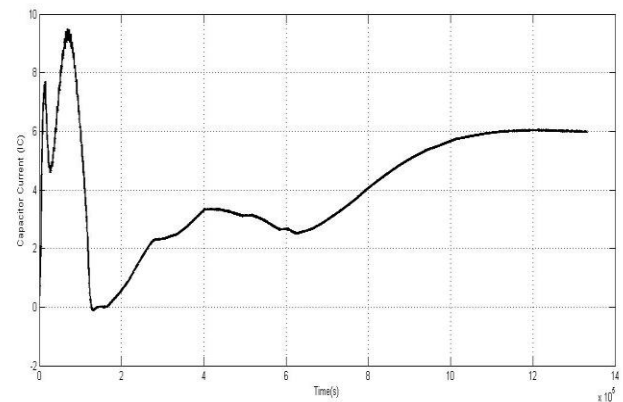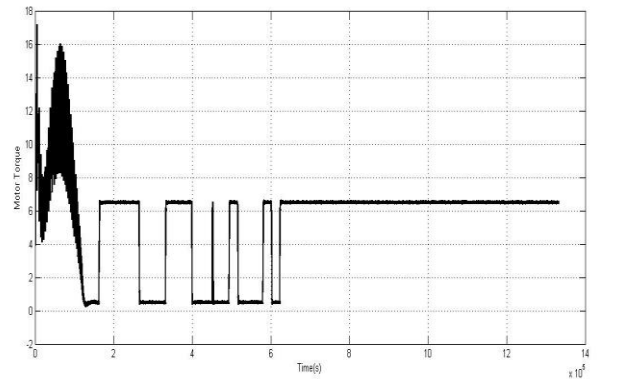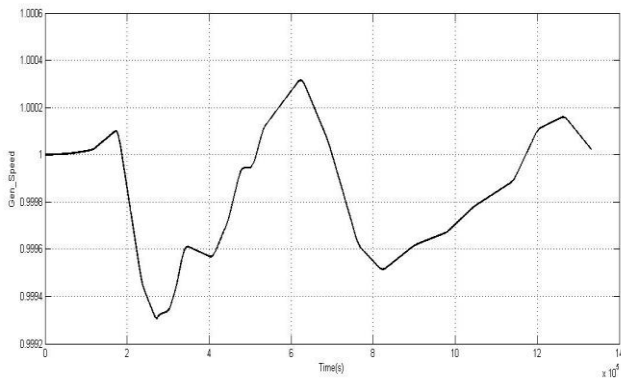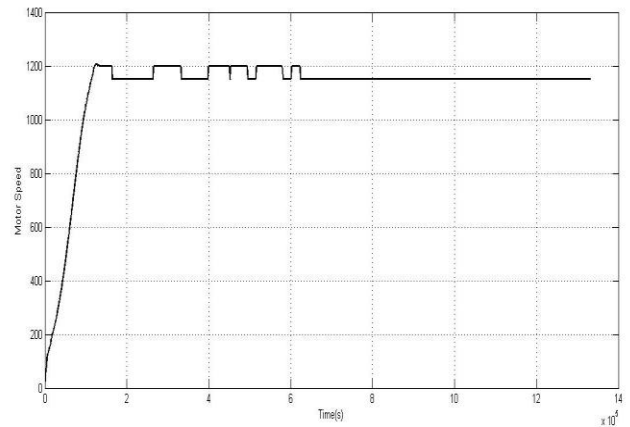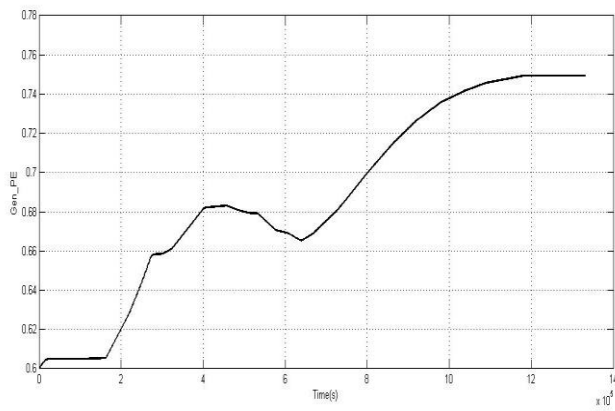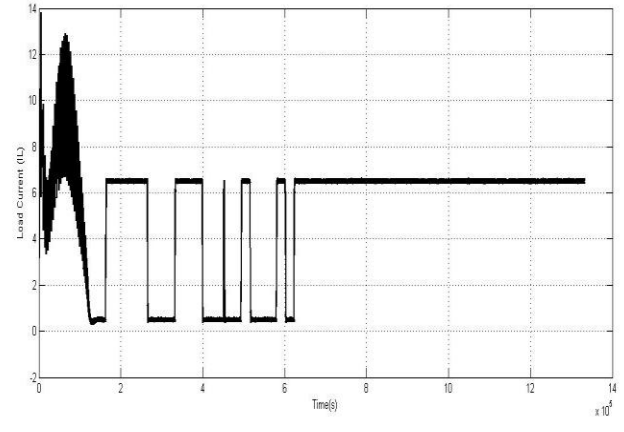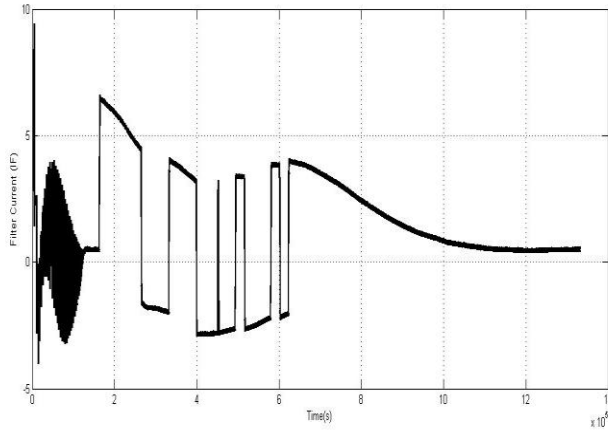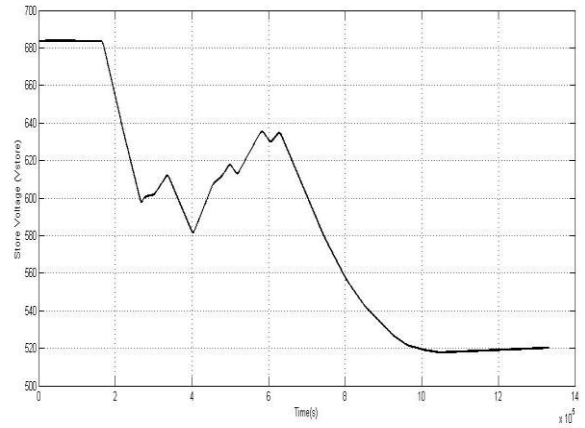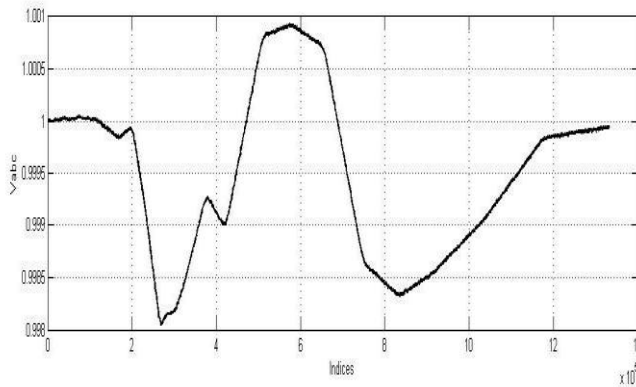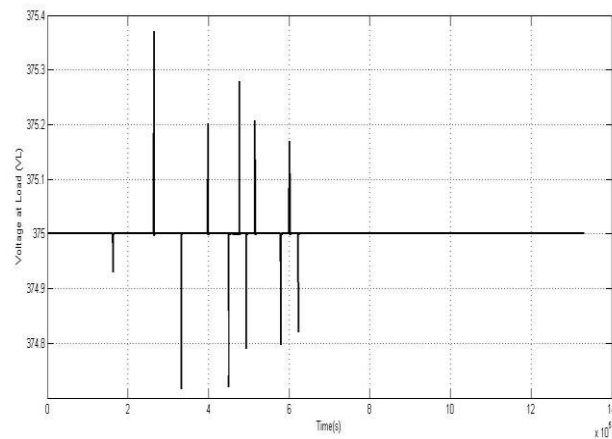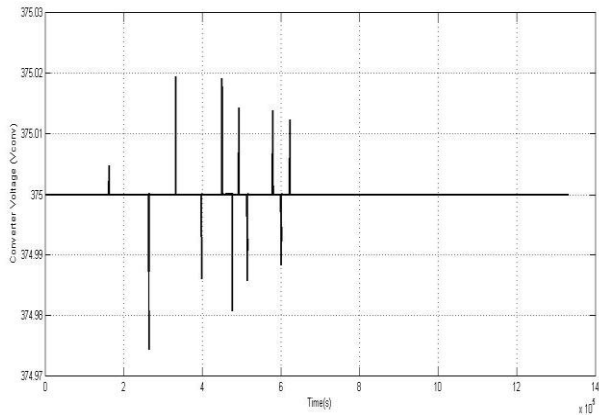
Figure.5.3 Waveforms of induction motor using APS

V.   CONCLUSION

The Adaptive Power System (APS) concept presented in this paper 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. 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. In addition, because of the linear behaviour of the outer-energy loop regulation technique, performance is maintained overall operating conditions. The APS shapes the dynamics seen by the generator to be slower than the response times of the prime-mover's speed or generator's voltage regulation loops, thus allowing the genset to maintain speed and voltage regulation during these large load dynamics. Not only can the APS help to maintain generator/prime-mover reliability, but the APS can also be used to improve sensor/weapon performance or improve metrics such as system weight, cooling demands, and ship fueling costs. Performance of the APS has been demonstrated through the use of Matlab Simulink simulations. Calculated losses and size of a 300-kW system have also been provided, demonstrating that the APS is a viable solution for integrating high-energy sensors and weapons onto Navy platforms.

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