A Study of Electric Power Distribution Architectures in Shipboard Power Systems

ABSTRACT

In this paper, various power distribution architectures that can be implemented on a shipboard power system are investigated. The paper implements various distribution system architectures including; Radial AC, Medium Voltage DC and Zonal DC distribution systems on a reduced scale laboratory test-bed. A detailed comparison among these architectures was conducted during simulated ship sailing and on-shore operation as well as in emergency situations. The paper also identifies the pros and cons of the distribution system architectures under study. The conclusions were supported by simulation and initial experimental results. A case study of a shipboard power system encountering a heavy load featuring set of pulses loads was investigated. The implemented example system included a hybrid storage system involving batteries and super capacitors. The results show the effectiveness of each architecture as well as the importance of the real time energy management algorithm.

INTRODUCTION

New Generations of naval ships employ an integrated power system featuring hybrid electric drive propulsion. In such a system, propulsion motors, power conversion and distribution networks, service and hospitality loads in addition to mission loads are supplied by an integrated electric shipboard power system [1]. An advantage of integrated power systems is the flexibility to shift the power between the propulsion and mission-critical loads as needed. This system involves distributed generation, energy storage, system automation, network reconfiguration, dynamic power allocation, and condition-based maintenance [2]. Shipboard power system loads have different types and characteristics. Their level of priority is an essential factor. The quality, efficiency and reliability of their supply are dependent on the power system architecture. Therefore, careful attention is paid to the shipboard power system architecture in terms of system control, protection, stability, reliability, efficiency and pulsed load mitigation as well as restoration capability [3]- [6]. In this paper, a study aiming at finding the optimum distribution system architecture that would satisfy system performance under normal and abnormal operational conditions on a shipboard power system is presented. Moreover, system components such as sources/storage elements that are needed within these configurations to increase the reliability, stability and security are investigated. Finally, the effect of pulse loads on shipboard power systems and their mitigation was studied. A real-time energy management algorithm (RTEMA) aiming at reducing the overall energy cost and mitigating pulsed loads effects was developed here.

IMPLEMENTATION TEST-BED

The real-time operation of this system was presented. For experimental testing, some of the ideas and aspects investigated in this paper were implemented on the hybrid AC/DC power system test-bed developed at the Energy Systems Research Laboratory (ESRL), Department of Electrical and Computer Engineering, Florida International University. This test system has an operating capacity of 36 kW on the AC side representing four AC generators and 36 kW on the DC side from energy storage. The laboratory design and its control was carefully equipped and prepared such that it can effectively emulate a shipboard power system but at a reduced laboratory power level. Hence, this adds to the credibility of the results obtained and the conclusions derived in the paper.

ARCHITECTURES IMPLEMENTATION

In this paper, we will compare four distribution architectures that may be used on a shipboard power system. These architectures are the Radial AC, Medium
Voltage DC and Zonal DC distribution systems and they will all be implemented on the shipboard power system test-bed mentioned above. This test-bed has a total generation capacity of 36 kW of energy assets on the AC, in addition to 36 kW on a DC microgrid infrastructure. The system involves bus models, cable models and measurement devices. The complete details of this test-bed can be found in [7]-[8]. Figure 1 shows a general overview of the infrastructure planned for the for the implementation of the distribution architectures on this test-bed. The implementation system consists of 5 busses; four of which are AC buses and bus 5 represents the microgrid featuring a DC bus with all load models, storage and control systems. Each of the AC busses consists of a prime mover-generator set cascaded by two possible paths for the power entering the bus giving two options. If $S_{ac}$ is ON and $S_{dc}$ is OFF, the power will flow in an AC form to the bus. However, if $S_{dc}$ is ON and $S_{ac}$ is OFF the power will flow to the bus through an AC/DC rectifier yielding DC power. This flexibility of supplying the system with AC or DC power allows the reconfiguration of the system to test different architectures. The DC microgrid involves fuel cell generation, battery storage and super capacitors. The $S_{ac}$ and $S_{dc}$ do the same role here as explained earlier. The switches designated S1 though S8 give more flexibility and reconfiguration capability to the system.

![Fig. 1. Shipboard Power System under Study](image1)

**a) AC Radial Distribution**

In this architecture, the power flows in a radial manner. Every bus is just connected to the bus/buses physically existing around it. This will be implemented on the test-bed by switching control of switches S1, S3, S6, S8 and $S_{ac}$ ON. Also by switching S2, S4, S5, S7 and $S_{dc}$ OFF. Figure 2 shows the power flow in the test-bed with the radial architecture implemented.

![Fig. 2. Radial AC distribution.](image2)

**b) Medium Voltage DC Distribution**

Medium voltage DC power distribution systems are being considered for future naval warships. There are several design considerations attached to them. In this case, all the generators will be sharing DC power. This will be implemented on the test-bed by switching S1 through S8 and $S_{ac}$ ON; and switching $S_{ac}$ OFF. Figure 3 shows the power flow in the test-bed with this DC distribution architecture implemented.

![Fig. 3. Medium voltage DC distribution.](image3)

**c) AC Zonal Distribution**

In zonal architectures, the generator in a zone supplies the load within that zone, and shares its power when needed with other zones. This has an advantage in terms of protection limiting a fault taking place in a zone from propagating to the rest of the system. The zonal approach also has an economic impact in reducing the operating costs. This will be implemented on the test-bed by switching $S_{ac}$ ON; and switching S1 through S8 and $S_{dc}$ OFF. Figure 4 shows the power flow in the test-bed with an implementation of this architecture.

![Fig. 4. Zonal AC distribution.](image4)
d) DC Zonal Distribution

This case is similar to the zonal AC distribution. However, the power here is transferred in the form of DC using rectifiers [9]. This will be implemented on the test-bed by switching $S_{ac}$ ON; and switching $S1$ through $S8$ and $S_{dc}$ OFF. Figure 5 shows the power flow in the test-bed with the zonal DC distribution architecture implemented.

ARCHITECTURES RESPONSE TO A PULSED LOAD ON BUS 5

In order to investigate the various architectures, their performance under pulsed load condition is examined. The pulsed load implemented was connected at bus 5. This load has an amplitude of 30 kW and a duration of 0.2 s. Figures 6-9 show the performance of the radial AC distribution, medium voltage DC distribution, zonal AC distribution and zonal DC distribution, respectively. The maximum voltage drop for these architectures was observed. It can be seen that DC architectures generally encounter relatively less voltage drop due to the absence of the inductive drop in the lines. It can be also be noticed that the zonal architectures, beside the fact that they have higher efficiency, have less voltage due to the deactivation of the connecting lines between the zones.

REAL-TIME OPERATION AND PULSED LOAD MITIGATION

In this section, we will investigate the importance of having certain assets available on the shipboard power system that is dealing with service and hotel loads in addition to pulsed loads. The performance of a fully integrated ship power system is analyzed. There are particular loads on shipboard power systems such as electromagnetic launch systems and free electron lasers, which draw very high short time current in an intermittent fashion [8]. In this paper, the power system was thoroughly simulated to capture its transient and dynamic behaviors during the occurrence of a pulsed load. Then, the importance of implementing a real-time energy management procedure was discussed. The main objective of the real time energy management algorithm is the mitigation of pulsed loads [9]. Therefore, we can define two main modes of operation namely; the pulsed load mitigation mode and the normal operation or cost minimization mode. An example hybrid AC/DC system resembling a shipboard power system was simulated. This example system is shown in figure 10 shows scaled down ratings for implementation in the laboratory test setup.

Fig. 6. Radial AC architecture response.

Fig. 7. Medium voltage DC architecture response.

This system includes two 13.8 kW main generators (MTG) and two 10.4 kW auxiliary generators (ATG) connected in a ring bus configuration. The bulk of the load consists of two 50 kW propulsion motors, modeled as permanent magnet machines supplied by PWM drives, with hydrodynamic propeller models as the mechanical load. Each rectifier supplies one of two
0.318 kV DC busses. The DC distribution zone is supplied by one of the two available rectifiers. Although various models for the loads may be used, constant impedance models were used in this paper.

Furthermore, a fuel cell (FC) system of 10 kW rated capacity, lithium-ion batteries with 3000 Ah rated capacity and a super capacitor with 200 F were included in the DC microgrid. A PWM controlled DC-DC converter was used as an interface between the FC system and the DC bus. Moreover, a vector decoupling PWM controlled AC-DC/DC-AC bidirectional converter was used for connectivity between the AC and DC sides of the grid. In the steady state case, the system voltages and loadings are within the normal limits.

A. Super Capacitors are always Fully Charged to Mitigate Possible Pulsed Loads

In order to achieve this in real time, the amount of energy available in the super capacitor must be monitored and compared to the energy that would be available in fully charged super capacitors to assure having all the super capacitors initially charged and ready to operate. If the super capacitors are not fully charged, in case they are connected to the DC bus through a DC-DC converter, they are immediately charged using the batteries and/or the grid power according to the availability of energy in the battery. If the Li-ion Batteries have Enough energy to help Super capacitors mitigate pulsed loads

B. Normal Loads on the DC are Supplied Using FC System Operating at its Maximum

For transient simulations, we considered a pulsed train of four pulses with a rate of 0.2 Hz, a duty ratio of 10% and amplitude of 20 kW. As explained earlier, if there is a pulsed load predicted to take place, the real time energy management algorithm should assure that the battery is fully charged to assist the super capacitors mitigate the effect of pulsed loads on the electrical power system, especially on the AC side. In order to verify the validity of the algorithm, two cases were investigated; the case when there is a pulsed load while the proposed algorithm is implemented (Case 1)
and another case when the occurrence of pulsed loads was not predicted and/or planned for, while dealing with the charge/discharge process of the batteries. The main difference between these two cases is that in the first case, the batteries are ready and fully charged when the pulsed load takes place. Whereas, in the second case the battery State of Charge (SoC) is independent and random. This means that the charge/discharge process of the batteries is based on other factors (Case 2).

**Case 1: Fully Charged Battery**

In this case, the real time energy management algorithm assures that the batteries are fully charged and will be available during the occurrence of the pulsed loads. Figure 11 shows the active power of the pulsed load and the power sharing among the AC generators, super capacitor and battery.

![Fig. 11. Active power of the pulsed loads and the power sharing among AC generators, super capacitor and full-charged battery (Case 1).](image)

Initially, the battery is not injecting any power to the DC bus since it is dedicated to mitigate the pulsed load. Hence, the battery voltage is maintained at the same voltage level of the DC bus. At the beginning of the pulsed load, the super capacitor satisfies the whole demanded power because of the high rate of discharge. Then, the battery starts to increase the injected power to the demanded pulse, while the power share from the super capacitor is exponentially decaying. Therefore, the sizing of the battery and the super capacitor is a very crucial subject in the design of hybrid microgrids with pulsed loads. According to inertia time constant of the AC generators, they start to maintain the system frequency at 60 Hz and react to the pulsed load. This can be seen by noticing the oscillations of the AC generators’ power. By the end of the first pulse, the battery will discharge energy to the DC bus due to the drop of its voltage level, which needs some time to recover as shown in Fig. 11. Because of the oscillations in the AC generation, the DC bus voltage oscillates between the pulses. Hence, the super capacitor power charges and discharges before the next pulse as well. This will also affect the battery power as can be seen in Fig. 11. Following the passing the four pulses, the system comes back to its initial steady state condition.

**Case 2: Half Charged Battery**

In this case, we assume that the energy available in the battery is just enough for the first two pulses of the pulse train, which represents the case when the SoC drops to its lower limit following the second pulse. Technically, this means that the battery voltage will dramatically drop after the second pulse and the converter controller will disconnect the battery from the DC bus. Fig. 12 shows this situation in terms of generation and load levels.

![Fig. 12. Active power of the pulsed loads and the power sharing among AC generators, super capacitor and half-charged battery (Case 2).](image)

Following the second pulse, the battery injected power is zero, and then the AC generators are totally responsible for the next two pulses. As can be seen, there are large oscillations in the AC generation levels and the super capacitor’s power. The DC bus voltage drops to 0.823 p.u. because of the effect of the pulsed load. The voltage changes in the buses depend on the pulsed load parameters such as the magnitude of the pulse, its duration and the number and level of the pulses. The voltage controller parameters, such as the AVRs settings of the generators also affect the system behavior during pulse load conditions, and following its clearance. One of the key factors of transient stability is the rotor angle of each generator during and after an
event such as a pulsed load. During the pulsed load, the power and angle jump to a new operating range for both generators. After the end of the pulsed load, the power and rotor angle return to their normal values with some oscillations around the steady state values. The magnitude and duration of these oscillations depend on the system inertia, the generator voltages and the power controller parameters.

Figures 13 and 14 show the transmitted power versus rotor angle of the main generator during the pulsed load for Cases 1 and 2, respectively. The amplitude of the transferred power in Case 2 and the rotor angle changes during the pulses are more than Case 1 due to the absence of battery energy for last two pulses. However, the system remains stable and the rotor angles return to the steady state point.

Fig. 13. Power-Delta Curve for main generator during Pulsed Load (Case 1).

Fig. 14. Power-Delta Curve for main generator during Pulsed Load (Case 2).

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CONCLUSIONS

In this paper, various power distribution architectures that can be used on shipboard power systems were investigated and compared. The available assets that need to be available on shipboard power systems to handle the various of loads or scenarios were discussed. An example of a system encountering normal and pulsed loads conditions simultaneously was analyzed. This example helped emphasize the importance of having a real-time energy management algorithm to manage these assets to mitigate the pulsed load conditions. We developed a real-time energy management algorithm to mitigate these pulsed loads effects on the system performance in smart microgrids. The main objective of the algorithm is to manage the energy storage devices in real-time in order to maintain system stability and performance in the short term operation and minimize the energy cost in the long term operation particularly for peak shaving purposes. An investigation on the system performance under pulsed load shows that when the battery’s state of charge was managed by the developed algorithm, the system has better stability margin and the battery is sustained to share all its stored energy for the pulsed loads. The comparison with the system performance without fully charged battery results in more system parameters changes. This may cause stability problem or system protection reaction due to the high drop in frequency/voltage and hence the system may be thrown off-line in an outage state.

REFERENCES


