

# FLYWHEEL BASED ENERGY STORAGE SYSTEM FOR VOLTAGE SAG CORRECTION AND DETECTION

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**Abstract:** A shipboard power system is a stiff, isolated power system. Here Power is generated locally, and distributed over short distances making the system vulnerable to transients. Power quality problems such as voltage sags, arising due to a fault or a switching load, can cause interruptions of critical loads. This can be of a serious concern for the survival of a combat ship. To mitigate voltage sags, flywheel energy storage system can be used for parallel voltage injection type . The basic circuit consists of an energy storage system, power electronic interface and a parallel connected transformer. The energy storage system consists of a flywheel coupled to a separately excited DC machine. The power electronic interface consists of a voltage sourced converter (VSC) connected to a DC motor. The flywheel stores energy in the form of kinetic energy and the DC machine is used for energy conversion. Bi-directional power flow is maintained by regulating the DC voltage. Sinusoidal PWM is used for controlling the power system side VSC. Present research work presents modelling, simulation (using MATLAB) and analysis of a flywheel energy storage system (FESS) based static parallel compensator for voltage sag correction with a power converter interface. The detailed models of a separately excited DC machine, rectifier and inverter are presented and the simulated performance of the flywheel energy storage system in mitigating balanced voltage sag is analyzed.

## I. INTRODUCTION

Flywheels is being used as mechanical energy storage devices since long time. This is the earliest form of a flywheel which is called as potter's wheel that uses stored energy to help in shaping earthen vessels. The energy stored in a potter's flywheel is almost 500J, which can by no means be neglected. The main disadvantages are friction and material integrity [1-1]. Most of its energy is lost in overcoming frictional losses [5-2]. The same concept can be used to store energy

in form of kinetic energy and to be utilized after energy conversion.

The flywheel energy storage system has three modes of operations:

- Charge mode
- Stand-by mode
- Discharge mode

When in charge mode, one VSC interfacing the DC machine runs as a rectifier and transferred energy accelerates the flywheel to its rated speed and energy is stored in the flywheel in the form of kinetic energy. The energy flows from shipboard power system to flywheel with DC machine acting as energy converter [3-3]. As soon as the flywheel reaches the charge speed, the storage system comes in standby mode and is ready to discharge when the critical load observes a voltage sag. In this mode a little energy from the shipboard power system is used for meeting the converter and machine losses. During discharge mode, the VSC interfacing the shipboard power system runs as an inverter injecting the required voltage in series with the line to correct the voltage sag. The flywheel slows down as it discharges. In this mode, the stored energy is used for sag correction and energy flows from the flywheel to shipboard power system [4].

## II. VOLTAGE SAG

Voltage sag can be observed as a short duration phenomenon at power system frequency resulting in a decrease in the RMS voltages of magnitude from 10% to 90%. It lasts typically about half a cycle to a minute [5]. Adjustable speed drives, computers process control equipment, etc which are variable in nature are

sensitive to these voltage sags. Loads may mis-operate or trip even for voltage sag of 10%, lasting two cycles. Process industry applications such as paper mills and semiconductor fabrication plants may take a lot of time to restart when tripped. Being production oriented, the impact of the voltage sag is very significant. Electrical distance to the point of cause determines depth of the sag. The starting current of a large induction machine is typically 6-12 (starter compensators reduce it to 3-6) times the rated current when line started. The voltage drop caused by this starting current is the same in the three phases causing balanced voltage sag. The voltage drops suddenly and recovers gradually as the machine reaches its rated speed. The same behaviour can be observed for large synchronous motors as most of them start as induction machines before synchronization.

The inrush current due to the energizing of a large transformer is typically 5 times the rated current. The different voltage drops in each phase, result in unbalanced sag. As the transformer reaches its rated flux the voltage recovers gradually. The majority of voltage sags are due to electrical faults. Unlike the starting of large machines, voltage sags due to electrical faults are unpredictable. Loads connected to the feeders that contribute current to the fault experience a voltage sag, when a fault occurs in a power system. In addition, loads downstream from the fault, or from junctions to the faulted feeder, also experience a voltage sag, making voltage sag a global phenomenon, compared to interruption where the isolation of faulted feeder causes a local disruption. The severity of the sag depends on the amount of fault current available at that feeder. In other words, the number of loads affected by voltage sags depends on the source impedance.

A voltage sag can generally be characterized by depth and duration. The depth of the sag depends on the system impedance, system characteristics (grounded or ungrounded), fault distance, and fault resistance. The duration of the sag depends on the time taken by the circuit protection to clear the fault. It is desirable to have high speed tripping to limit the duration of sags.

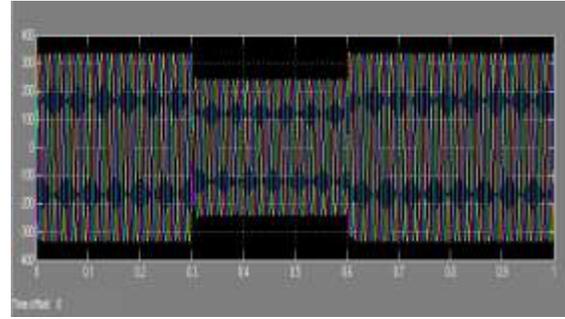


Figure: 1. Representation of Voltage Sag

### III.SAG DETECTOR

The Sag Detector modelled in MATLAB detects the voltage sag in the Shipboard Power System. It takes two voltages in its input: Line voltage from the Power Supply side and Load Voltage from the Critical Load. The line voltage is used to calculate the magnitude of voltage sag in the transmission lines. This magnitude helps us to select the components of critical load of suitable ratings. The Load Voltage is further given to the Sag Corrector which compensates the voltage sag on the critical load side.[6]

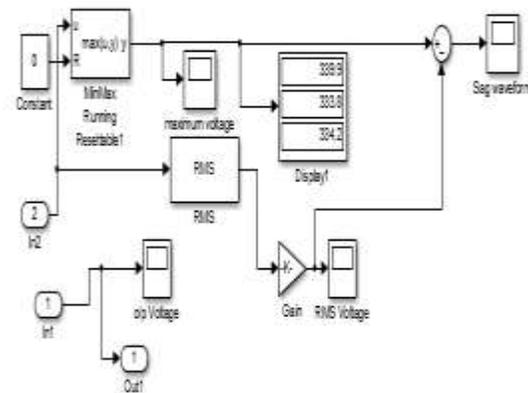


Figure 3: Model of Sag Detector

### IV.SAG CORRECTOR

The Sag Corrector collects the Load Voltage from the Sag Detector which is supplied to the PWM block which generates gate pulses. These gate pulses are then applied to the 3-phase Inverter which takes its DC supply from the DC Motor Armature terminals at the time of voltage sag. Due to inertia, the flywheel keeps rotating and the mechanical energy of the flywheel is

converted to electrical energy at the armature terminals. This DC voltage is then inverted to AC and is injected to the transmission line supplying the critical load through a non linear parallel 3 phase transformer. Thus the detected sag in the side of critical loads is corrected.

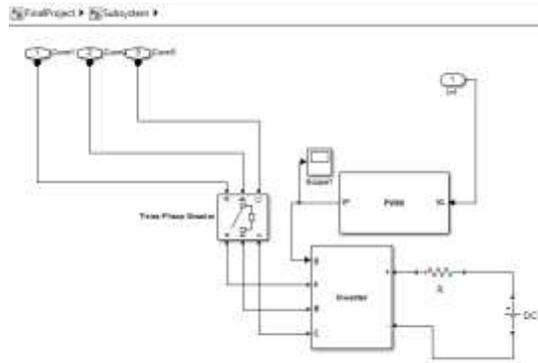


Figure 4: Sag Corrector

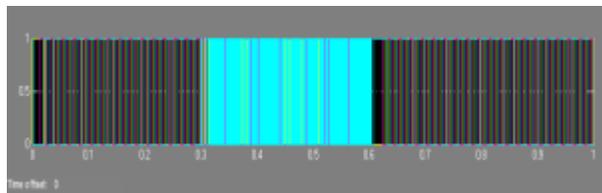


Figure 5. Input gate pulses to Inverter

### V.SIMULATION AND RESULTS

The Flywheel based energy storage system was modelled and its performance was analyzed by creating a three phase fault at the location shown in the figure.

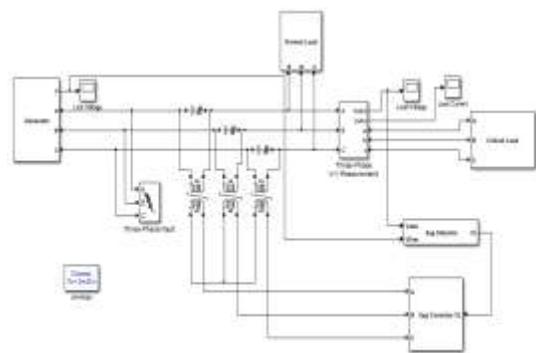


Figure 6: Flywheel Energy Storage System Model

The figure 7 shows phase to ground voltages at the power system side of the model.

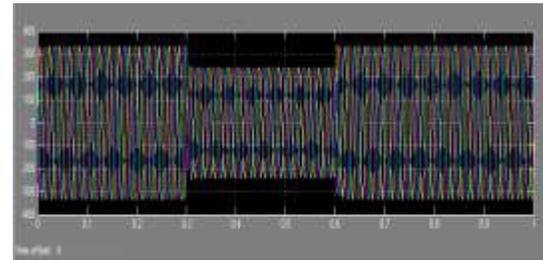


Figure 7: Phase to ground voltages at SPS side

The source side voltage is seen dropping by a noticeable amount which constitutes voltage sag. This sag may be a threat to the critical equipments which are necessary to be operating strictly at all times to ensure the survivability of the combat ship. The fault here shown is a 3-phase symmetrical fault which results in the equal drop in magnitude in the 3 phases.

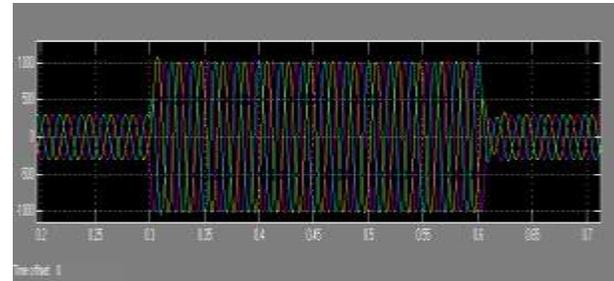


Figure 8: Currents at the SPS side

The decreased magnitude of 3 phase voltage is accompanied by an increase in 3 phase currents across the line. These over currents may damage the insulation and may cause damage to the components of critical load.

The sag detector detects the Voltage Sag and produces a waveform which is further used to select the critical load components of suitable ratings. It is shown as the difference between the maximum magnitude of source voltage and the rms voltage at the load side.

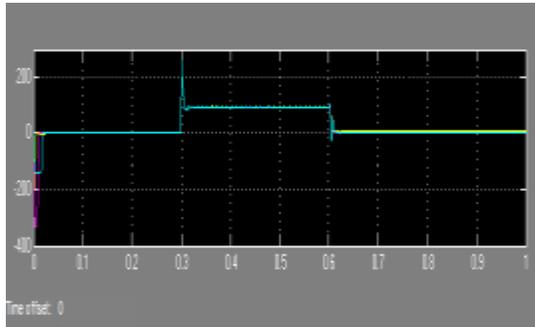


Figure 9 Waveform of Voltage Sag

The Sag Corrector is activated simultaneously and uses the voltage at the critical load side to generate gate pulses for the Inverter. Here, the sag correction is done for 0% tolerance, i.e. the compensated voltage at the duration of sag makes the load voltage exactly equal to the pre sag voltage.

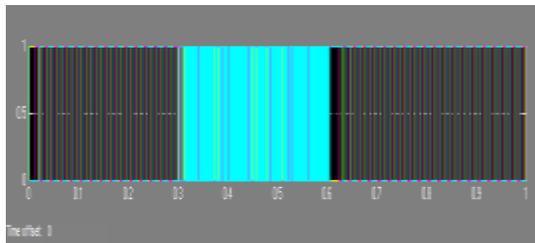


Figure 10 Gate pulses fed to Inverter

The DC Motor with the flywheel mounted on its shaft attains its rated speed in the pre sag interval. Once it attains its rated speed, it continues to rotate and now is in the stand-by mode. At the instant of sag, the flywheel which had stored energy in it in the form of rotational kinetic energy keeps on rotating due to inertia and the voltage across armature terminals is now due to conversion of mechanical energy from the flywheel to electrical energy.

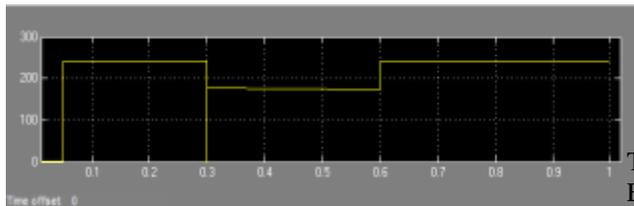


Figure 11 Voltage across DC Motor Armature terminals

This DC Voltage is fed to the two terminals of the Inverter which generates an AC Voltage which is fed to the circuit using a 3 Phase Non-Linear transformer which corrects the Voltage Sag. The Sag Compensation is done at 0% tolerance. But this is causing overvoltage at the end instant of the voltage sag which is undesirable. The compensation can be done at 5% tolerance but then it causes fluctuations in the post sag voltage which is more undesirable.

Figure 11 shows the corrected Voltage at the Critical load side.

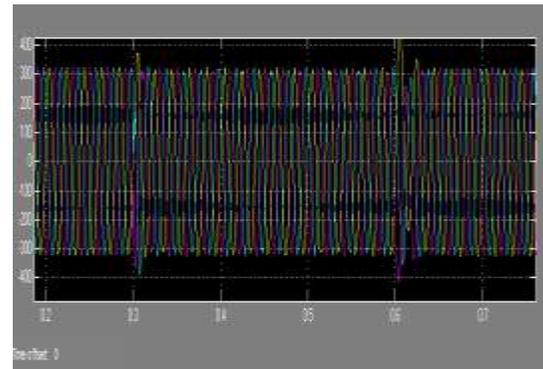


Figure 12: Corrected voltage at Critical load side

Figure 12 shows the corrected Current at the Critical load side.

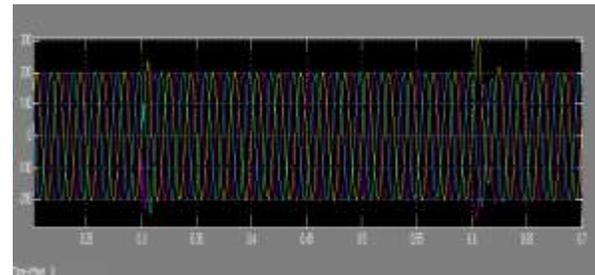


Figure 13 Corrected Current at the Critical load side

## VI. CONCLUSION AND FUTURE SCOPE

The modelling and analysis of the Flywheel Energy Storage System for Voltage Sag Detection and Correction in a Shipboard Power System is done using MATLAB/Simulink. A control scheme has been proposed for voltage sag correction and energy control. The

Simulation results show that a flywheel mounted on a DC Motor at the critical load side is an efficient way to mitigate voltage sags.

The results also imply that there is no power injection initially since the injected voltage is in quadrature with line current. During voltage sag correction the phase angle is almost in phase thereby allowing energy to flow into the shipboard power system.

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