CHAPTER 5

GEO LIFE TESTING AND MODELING

5.1 INTRODUCTION

The GEO satellites are widely used in applications such as communication, military, and metrological systems. In GEO satellites, the batteries are seasonally used. The total useful time is less than 1% of the lifetime of the satellite. There will be two eclipse seasons in a year extending for 45 days. Only 90 days in a year the batteries are used in GEO. During other periods, the battery is dormant. Even during the 45 days eclipse, the eclipse duration increases from 10 minutes to a maximum of 72 minutes and falls back again. So the number of cycles is very few. In a 15 year period, the batteries will undergo a maximum of 1350 charge discharge cycles. For this reason, the batteries are allowed to go for DOD of 60% to 80% in GEO spacecrafts. In GEO spacecrafts battery degrades both due to cycling as well as storage/calendar life when the batteries are not at all used. GEO space craft batteries have sufficient time for recharging the batteries. To utilize the full duration available for charging the batteries, generally low charge rates are used. The solar array size will be small for low charge currents. If the charge currents are high then it leads to very large size solar array that is not economical.

In this chapter, the experiments conducted on Lithium-ion battery to estimate RC and to develop a model to assess the capabilities of it to perform in GEO conditions are presented. Experimental results are used to model and
predict the cell performance and degradation with storage / calendar life and cycling. The following tests are conducted and models are developed.

1. Effect of SOC and Temperature on RC during storage/calendar life period over seven and half years.

2. Effect of Temperature, charge discharge cycling on RC and EODV at peak DOD with variable DOD cycling for 2000 cycles.

5.2 GEO STORAGE/CALENDER LIFE TEST AND MODELING

In GEO satellites the Lithium-ion batteries are not used during solstice period. Solar panels support the total loads during solstice. During this period, the batteries will be on open circuit stand. So the capacity fading is only due to the storage / calendar life. Capacity fading due to cycling is not applicable during this period. Storage / calendar life degradation is associated with the critical operating parameters such as SOC and the temperature.

Calendar life tests have been continuously generating data for seven and half years with the cells tested for the SOC of 25%, 50%, 75% and 100% for various temperature settings of 0°C, 10°C, 20°C, 30°C and 40°C to study how the battery would behave under different solstice conditions.

RC has been measured under standard conditions at the interval of six months and the resulting data sets of 288 patterns that are generated for the various SOC at different temperatures mentioned earlier have been used in designing and training of the different models.

5.2.1 MR Model Description and the Results for GEO Storage/Calendar Life Test

MR model has been designed with the given data sets derived from experimental results of GEO storage/calendar life test to find the RC at different SOC and Temperature over the period of seven and half years. The
independent variables are Temperature, SOC and Test duration with RC as the dependent variable. The estimated MR model with R-Squared value of 0.8746 is given in the Equation (5.1).

**Estimated model for RC**

\[
RC = 107.734 - 0.113 \times T - 0.129 \times SOC - 1.164 \times TD
\]  

(5.1)

The observed and predicted values of RC from MR model for GEO Storage / calendar life test at various SOCs and Temperatures are shown in the following Figures. Figure 5.1(a-c) shows the observed and predicted values of RC from MR model at different charge rates of 25%, 50% and 75% for the temperatures 0°C, 10°C, 20°C, 30°C and 40°C. Figure 5.1(d) shows the observed and predicted values of RC from MR model at 100% charge with temperatures 0°C, 10°C and 20°C. The comparison graph between the observed and predicted values of RC from MR model is given in the Figure 5.2(a). The Bland Altman Plot between the observed and predicted values of RC from MR model is given in the Figure 5.2(b).

![Figure 5.1](image.png)  

(a)  

(b)

**Figure 5.1 (Continued)**
Figure 5.1  Observed and predicted values of RC from MR model with SOC of (a) 25% Charge, (b) 50% Charge, (c) 75% Charge and (d) 100% Charge at various Temperatures for GEO storage / calendar life test

Figure 5.2  (a) Comparison graph and (b) Bland Altman Plot between observed and predicted values of RC from MR model for GEO storage / calendar life test
5.2.2 MVRPF Model Description and the Results for GEO Storage / Calendar Life Test

Multivariate Ratio of Polynomials search has been performed to find the best fit model for the given data sets derived from GEO storage/calendar life test to find the RC. The independent variables transformation to get the best fit model with R - squared value of 0.9664 to estimate the dependent variable RC is Temperature= T, State Of Charge = SOC, Test Duration = SQRT(TD). The estimated model for RC is given in Equation (5.2).

**Estimated model for RC**

\[
\text{RC} = ((100.8) -(1.63)*T+(6.43E-03)*T^2-(1.26)*SOC+(9.63E-03)*T*\text{SOC}+(3.82E-03)*\text{SOC}^2-(16.04)*(\text{SQRT(TD)})+(0.14)*T*\text{(SQRT(TD))}+(0.12)*\text{SOC}*(\text{SQRT(TD)})+(0.48)*(\text{SQRT(TD)})^2)/(1-(1.61E-02)*T+(6.32E-05)*T^2-(1.24E-02)*SOC+(9.4E-05)*T*SOC+(3.71E-05)*\text{SOC}^2-(0.15)*(\text{SQRT(TD)})+(1.321E-03)*T*(\text{SQRT(TD)})+(1.22E-03)*SOC*(\text{SQRT(TD)})+(5.082E-03)*(\text{SQRT(TD)})^2)
\]

The observed and predicted values of RC from MVRPF model for GEO Storage / calendar life test at various SOCs and Temperatures are shown in the Figure 5.3. Figure 5.3(a-d) shows the observed and predicted values of RC from MVRPF model for SOC of 25%, 50%, 75% and 100% at different temperatures respectively. The comparison graph and Bland Altman Plot between the observed and predicted values of RC from MVRPF model is given in the Figures 5.4(a) and 5.4(b) respectively.
Figure 5.3  Observed and predicted values of RC from MVRPF model with SOC of (a) 25% Charge, (b) 50% Charge, (c) 75% Charge and (d) 100% Charge at various Temperatures for GEO storage / calendar life test
Figure 5.4  (a) Comparison graph and (b) Bland Altman Plot between observed and predicted values of RC from MVRPF for GEO storage / calendar life test

5.2.3  Fuzzy Model Description and the Results for GEO Storage / Calendar Life Test

The experimental results of GEO storage/calendar life test to find the degradation in RC at various SOC and temperatures is used to design the Fuzzy model using Mamdani rule base. The three input parameters are namely Temperature, Charge and Test duration. Centraoid defuzzification method is employed to get the crisp output. The complete configurations of Fuzzy model to estimate the RC are

No of inputs = 3
No. of output = 1
No of membership function for input 1 = 5,
No of membership function for input 2 = 5,
No of membership function for input 3 = 9,
No of membership function for output = 14,
No of Fuzzy rules = 162,
Type of membership function = Guassian
Membership function plots for the inputs and output variables are given in Figure 5.5(a - d) and the estimated R-squared values between the observed and predicted values of RC is 0.9952.

![Figure 5.5 Membership function plots of Fuzzy model (a) Input 1 (Temperature), (b) Input 2 (SOC), (c) Input 3 (Test duration) and (d) Output (RC) for GEO storage / calendar life test](image)

The observed and predicted values of RC from Fuzzy model at various SOC of 25%, 50%, 75% and 100% with different temperatures are given in the Figure 5.6 (a - d) respectively. The comparison graph between the observed and predicted values of RC from Fuzzy model is presented in the Figure 5.7(a) and the Bland Altman Plot for the same is presented in 5.7(b).
Figure 5.6 Observed and predicted values of RC from Fuzzy model with SOC of (a) 25% Charge, (b) 50% Charge, (c) 75% Charge and (d) 100% Charge at various Temperatures for GEO storage / calendar life test
Figure 5.7  (a) Comparison graph and (b) Bland Altman Plot between observed and predicted values of RC from Fuzzy model for GEO storage / calendar life test

5.2.4 ANN Model Description and the Results for GEO Storage / Calendar Life Test

A feed forward error back propagation network with three neurons in the input layer representing Temperature, SOC and Test duration respectively is used. One neuron in the output layer represents the RC. Two hidden layers with nine neurons each are used in this ANN structure. The network has been trained with the data sets derived from seven and half years of test duration for the error target of 0.3%.

The weights and bias generated by this trained network is used to predict RC value for seven and half years of period. The estimated R-squared value between the observed and predicted values of RC is 0.9966.

Similar ANN architecture with data sets for 4 years test duration has been trained for error target of 0.5%. The weights and bias generated by this trained network is used to predict RC value for seven and half years of
period (extrapolation). The estimated R-squared value between the observed and predicted values of RC is 0.9437.

The observed and predicted values of RC from ANN model trained with seven and half years test duration for SOC of 25%, 50%, 75% and 100% at various temperatures are shown in Figure 5.8(a-d).

![Graphs showing observed and predicted values of RC for different SOC and temperatures](image)

**Figure 5.8** Observed and predicted values of RC from ANN model with SOC of (a) 25% Charge, (b) 50% Charge, (c) 75% Charge and (d) 100% Charge at various Temperatures for GEO storage / calendar life test
The observed and predicted values of RC for seven and half years period from ANN model trained with 4 years of data sets for various SOC 25%, 50%, 75% and 100% at different temperatures are in shown Figure 5.9(a-d). Figure 5.10(a) shows the comparison graph between observed and predicted values of RC from ANN model trained with seven and half years and four years. Figure 5.10(b) shows the Bland Altman Plot between observed and predicted values of RC from ANN model trained with seven and half years and four years.

Figure 5.9  Observed and predicted values of RC from ANN model trained with 4 years duration with SOC of (a) 25% Charge, (b) 50% Charge, (c) 75% Charge and (d) 100% Charge at various Temperatures for GEO storage / calendar life test
Figure 5.10  (a) Comparison graph and (b) Bland Altman Plot between observed and predicted values of RC from ANN model for GEO storage / calendar life test

5.2.5 ANFIS Model Description and the Results for GEO Storage / Calendar Life Test

The ANFIS model for GEO storage/ calendar life test to predict RC has three inputs. Each input is fuzzified with eleven guassian membership function. The output is linear with eleven membership function. The number of rules is eleven. The network has been trained with error goal of 0.01. After successful training with 10 epochs the error goal achieved is 0.2066. The estimated R-Squared value between the observed and predicted values of RC is found to be 0.9979.

ANFIS structure for GEO storage / calendar life test to estimate RC has been shown in the Figure 5.11(a) and the performance graph is shown in the Figure 5.11(b).
Figure 5.11 (a) ANFIS Structure for RC Estimator model and 
(b) Performance graph of ANFIS model for GEO storage / calendar life test

The observed and predicted values of RC from ANFIS model for GEO Storage / calendar life test at various SOCs and Temperatures are shown in the Figure 5.12. Figure 5.12(a-d) shows the observed and predicted values of RC for SOC of 25%, 50%, 75% and 100% at various temperatures. The comparison graph between the observed and predicted values of RC from ANFIS model is plotted in the Figure 5.13(a). The Bland Altman Plot between the observed and the predicted values of RC from ANFIS model is given in the Figure 5.13(b).

Figure 5.12 (Continued)
Figure 5.12  Observed and predicted values of RC from ANFIS model with SOC of (a) 25% Charge, (b) 50% Charge, (c) 75% Charge and (d) 100% Charge at various Temperatures for GEO storage / calendar life test.

Figure 5.13  (a) Comparison graph and (b) Bland Altman Plot between observed and predicted values of RC from ANFIS model for GEO storage / calendar life test.
5.2.6 Comparison of Results and Discussion of Various Models Designed for GEO Storage / Calendar Life Test

The tests for GEO storage/calendar degradation at various SOC and temperatures have been performed. From the test results it can be inferred that the degradation increases with SOC and temperature. The influence of SOC in degradation of the capacity is found to be large when compared to temperature. This can be observed from the Figure 5.12. Here, for a temperature of 10 °C at different charge rates of 25% , 50%, 75% and 100%, the degradation is found to be 3%, 5%, 11% and 18% respectively for storage period of seven and half years. Similarly for the same SOC at different temperatures, for example with SOC of 75%, the degradation for 0°C, 10°C, 20°C, 30°C and 40°C is observed to be 10%, 11%,13%,15% and 18% respectively. These examples justify that the influence of SOC on capacity degradation is higher compared to influence of temperature on capacity degradation. From the experiment’s results the minimum degradation is observed at 0°C with 25% charge and the maximum degradation of 20% is observed at 20°C with 100% charge. With increase of every 25% of charge the degradation almost doubles. This experiment clearly indicates the SOC and the temperature should be kept as low as possible for longer battery life. These experimental results should be combined with the degradation due to cycling to get the total degradation in GEO satellites. Models are developed with the results and the following section discusses the observations and predictions from the different models.

The observed and MR model predicted outputs for test conditions with various SOC and temperatures are shown in Figure 5.1. It is observed from Figure 5.1(a) that the predictions from 25% charge rates and 50% charge rates are even at beginning of test duration where the observed RC itself is above 100% and subsequently the predicted values take a linear path which is
not the actual case. In the case of 75% charge rate and 100% charge rate initial degradation predicted by the MR model is more than the observed value but subsequently graph is matching up to two years after which the deviation from the observed value is found to be more. This clearly indicates the nonlinearity with the state of charge for which the model is not able to cope. The R-Squared value between the observed and predicted values for the entire range of SOC and temperature is found to be 0.8746 but the difference in each point in terms of percentage in Bland Altman Plot is observed to be -5.5% to +8%.

MVRPF model outputs are shown in Figure 5.3. From the Figures it is interesting to observe that for all the SOC of 25%, 50%, 75% and 100% and for lower temperatures the observed and predicted values are in close agreement. But when the temperature increases the deviation starts increasing till four years, that is, it shows that the degradation is more than that of observed. Beyond four years the predicted degradation is less than that of observed. The R-Squared between the observed and predicted looks to be attractive at 0.9664 whereas the difference in percentage for each point is -6% to +3%.

Fuzzy model output shown in Figure 5.6 is found to be very much close in agreement for the entire range of SOC and temperatures except for 25% charge at 40°C. Even though from the Figure it appears that the predicted and observed values are very close, the difference is -1% to +1.5% in the Bland Altman Plot.

ANN model trained with seven and half year period of data sets and the prediction made for the same period with the observed values are shown in Figure 5.8. The visual inspection from this Figure reveals that ANN model shows excellent prediction accuracy for the entire range of SOC and temperatures. The deviation also for each point is less than ±1%. The
extrapolation test conducted to find the extrapolation capability of ANN by training the ANN with data sets for four years and predictions are made for seven and half years. The result is shown in Figure 5.9. From the Figure it is observed that the predictions are in close agreement with the observed values till five years and the deviation starts beyond five years. It is interesting to see the extrapolation at lower temperature is found to be good for almost all SOC. When the temperature is 40°C and 30°C the deviation is higher. From the Figures the predicted capacity fading is less than the observed value as the difference in percentage for all the points observed in the Bland Altman Plot shown in Figure 5.10(b) is from -9% to +1%. Because of this, the ANN extrapolation is acceptable for lower temperatures for all SOC limits and for the entire range of SOC and temperatures for the duration of five and half years.

ANFIS model predictions and observed values have been plotted in Figure 5.12. The ANFIS has been trained with different configurations and the best fit has been presented without over fit or under fit. The observed and predictions are having excellent agreement between each other and the variation between the observed and predicted for the entire range is less than ±1%.

From the different models developed and the predictions of capacity fading for storage /calendar life indicates that Fuzzy, ANN, ANFIS are showing accurate estimation with minimum deviation of ±1%. The extrapolation test with ANN definitely reduces the duration of test period and interestingly the extrapolation capability can be relied up on for two years duration beyond the training period. The error values between the observed and predictions by all the models using statistical analysis and the Bland Altman Plot are given in the Table 5.1.
<table>
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<th>S. No.</th>
<th>Model</th>
<th>Statistical Analysis</th>
<th>Bland Altman Plot</th>
</tr>
</thead>
<tbody>
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<td></td>
<td></td>
<td>R-squared value</td>
<td>Coefficient of Variation</td>
</tr>
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<td>MR</td>
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<td>0.0166</td>
</tr>
<tr>
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<td>MVRPF</td>
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<td>0.0095</td>
</tr>
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<td>Fuzzy</td>
<td>0.9952</td>
<td>0.0035</td>
</tr>
<tr>
<td>4</td>
<td>ANN (trained with seven and half years of data sets)</td>
<td>0.9966</td>
<td>0.0029</td>
</tr>
<tr>
<td>5</td>
<td>ANN (trained with four years of data set)</td>
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<td>0.0098</td>
</tr>
<tr>
<td>6</td>
<td>ANFIS</td>
<td>0.9979</td>
<td>0.0023</td>
</tr>
</tbody>
</table>

Table 5.1 Error values obtained from different models designed for GEO Storage / calendar life test.
5.3 GEO VARIABLE DOD CYCLING TEST AND MODELING

Batteries will be in operation only during equinox. There are two eclipse seasons in a year lasting for 45 days each. The test consisted of repeated sets of 45 cycles representing the increasing and decreasing discharge durations of eclipses over 45 day GEO eclipse seasons, with a maximum 72 minute duration. The eclipse duration varies parabolically during each season. It increases to a maximum of 72 minutes and falls again to zero. Due to this the batteries DOD also varies parabolically. The maximum DOD will be around 60% on the day when the eclipse duration is 72 minutes. During cycling the capacity fading is associated with the operating parameters such as charge discharge cycle, temperature and DOD. The End of charge voltage is constant as it has been charged to the rated voltage of 4.2V. The charging current is of the order of C/10 as there is large time available to charge the battery. The discharge rate is constant as the Satellites load is fairly constant throughout its life span.

The Real-time variable DOD test is conducted by accelerated testing. In order to accelerate the testing, Charge durations were reduced by increasing charge current, allowing on average of around hundred cycles a month to be accumulated. Testing was performed for temperatures of 20°C and 40°C. This test acceleration has been allowed to accumulate for about 1840 cycles, representing an excess over the 1350 cycles normally specified for a 15 year GEO mission. The RC and the EODV at peak DOD have been measured at the interval of every 230 cycles representing ten peak DOD cycles. Resulting Eighteen patterns for each RC and EODV are used to design and train the different modeling.

5.3.1 MR Model Description and Results for GEO Variable DOD Cycling

MR model has been designed with the data sets derived from experimental results to find the RC and EODV at peak DOD for GEO
variable DOD cycling. The independent variables are Temperature and cycle number. RC and EODV at peak DOD are the dependent variables. The estimated MR models for RC and EODV at peak DOD are given in the Equations (5.3) and (5.4) with R-squared value of 0.9119 and 0.9639 respectively.

**Estimated model for RC**

\[
RC = 93.317 + 0.13056 \times T - 7.15E-03 \times CY
\]  

(5.3)

**Estimated model for EODV**

\[
EODV = 3.4598 + 2.5119E-03 \times T - 1.4771E-04 \times CY
\]  

(5.4)

The observed and predicted values of RC and EODV at peak DOD from the estimated MR models are plotted in the Figures 5.14(a) and 5.14(b). The comparison graphs between the observed and predicted values of RC and EODV at peak DOD from MR model are given in the Figures 5.15(a) and 5.15(b). Figures 5.16(a) and 5.16(b) shows the Bland Altman Plot between the observed and predicted values of RC and EODV at peak DOD from MR models.

![Figure 5.14](image_url)

**Figure 5.14** Observed and predicted values from MR model (a) RC and (b) EODV at peak DOD at 20° C and 40° C Temperatures for GEO variable DOD cycling test
Figure 5.15  Comparison graph between observed and predicted values from MR model (a) RC and (b) EODV at peak DOD at 20° C and 40° C Temperatures for GEO variable DOD cycling test

Figure 5.16  Bland Altman Plot between observed and predicted values from MR model (a) RC and (b) EODV at peak DOD at 20° C and 40° C Temperatures for GEO variable DOD cycling test

5.3.2  MVRPF Model Description and Results for GEO Variable DOD Cycling

Multivariate Ratio of Polynomials search has been performed to find the best fit model to find the RC and EODV at peak DOD for GEO
variable DOD cycling test. The independent variable transformation to get the best fit model with R - squared value of 0.9886 to estimate the dependent variable RC is Temperature=SQR(T), Cycles=1/(CY*CY). The independent variable transformation to get the best fit model with R- squared value of 0.9854 to estimate the dependent variable EODV at peak DOD is Temperature=T, Cycles=LN(CY). The estimated models for RC and EODV at peak DOD from MVRPF models are given in Equations (5.5) and (5.6) respectively.

**Estimated model for RC**

\[
RC = ((-1.1E-05) + (2.63E-06) * (SQR(T)) + (SQR(T))^2-(2.27)*(1/(CY*CY))+(0.86) * (SQR(T)) * (1/(CY*CY))+(8.87E-02) * (1/(CY*CY))^2) / (1-(0.38)*(SQR(T))+(3.53E-02)*(SQR(T))^2 - (2.17E-02)*(1/(CY*CY))+ (8.57E-03)*(SQR(T))* (1/(CY*CY))- (4.7E-05)* (1/(CY*CY))^2)
\]  
(5.5)

**Estimated model for EODV at peak DOD**

\[
EODV= ((-8.1E-08) + (2.3E-10)* T + T^2+(2.1E-08)*(LN(CY))- (4.3E-11) * T* (LN(CY))+(1.28E-09) * (LN(CY))^2) / (1-(0.1)* T +(0.001)* T^2+(5.82E-09)* (LN(CY))- (1.39E-11)*T* (LN(CY))-(3.44E-10)*(LN(CY))^2)
\]  
(5.6)

The observed and predicted values of RC and EODV at peak DOD for GEO variable DOD cycling test are shown in the following Figures. Figure 5.17(a) show the observed and predicted values of RC from MVRPF model and Figure 5.17(b) show the observed and predicted values of EODV at peak DOD. The comparison graph and Bland Altman Plot between the observed and predicted values of RC and EODV at peak DOD from MVRPF model are given in Figures 5.18 and 5.19 respectively.
Figure 5.17  Observed and predicted values from MVRPF model (a) RC and (b) EODV at peak DOD at 20° C and 40° C Temperatures for GEO variable DOD cycling test

Figure 5.18  Comparison graph between observed and predicted values from MVRPF model (a) RC and (b) EODV at peak DOD at 20°C and 40° C Temperatures for GEO variable DOD cycling test
5.3.3 Fuzzy Model Description and Results for GEO Variable DOD Cycling

Fuzzy model is designed to estimate RC and EODV at peak DOD using Mamdani rule base for GEO variable DOD cycling. In this model Temperature, cycle numbers are the two input parameters. Centraoid defuzzification method is employed to get the crisp output. The complete configuration of Fuzzy model to estimate the RC and EODV at peak DOD are

No of inputs = 2  
No. of outputs = 2  
No of membership function for input 1 = 2,  
No of membership function for input 2 = 5,  
No of membership function for output 1= 5,  
No membership function for output 2 = 5,  
No of Fuzzy rules = 10,  
Type of membership function = Guassian
Membership function plots for the inputs and outputs are given in Figure 5.20(a - d). The estimated R-squared values between the observed and predicted values RC and EODV at peak DOD are 0.9535 and 0.9262 respectively.

![Membership function plots of Fuzzy model](image)

**Figure 5.20** Membership function plots of Fuzzy model (a) Input 1 (Temperature), (b) Input 2 (Cycles), (c) Output 1 (RC) and (d) Output 2 (EODV at peak DOD) for GEO variable DOD cycling test

The observed and predicted results for RC and EODV at peak DOD from Fuzzy model are given in the Figures 5.21(a) and 5.21(b). The comparison graph and Bland Altman Plot between the observed and predicted value of RC and EODV at peak DOD from Fuzzy model is plotted in the Figures 5.22 and 5.23.
Figure 5.21  Observed and predicted values from Fuzzy model (a) RC and (b) EODV at peak DOD at 20° C and 40° C Temperatures for GEO variable DOD cycling test

Figure 5.22  Comparison graph between observed and predicted values from Fuzzy model (a) RC and (b) EODV at peak DOD at 20° C and 40° C Temperatures for GEO variable DOD cycling test
Figure 5.23  Bland Altman Plot between observed and predicted values from Fuzzy model (a) RC and (b) EODV at peak DOD at 20° C and 40° C Temperatures for GEO variable DOD cycling test

5.3.4  ANN Model Description and Results for GEO Variable DOD Cycling

Two ANN models with feed forward Error back propagation network have been designed to estimate RC and EODV at peak DOD separately. Both the ANN models have two inputs in the input layer representing temperature and cycle number respectively. The output layer has one neuron in both the models representing RC and EODV at peak DOD. Two hidden layers with each nine neurons are used in both the ANN structure. Both the networks have been trained for error target of 0.3%. The RC and EODV at peak DOD is estimated using the weights and bias generated by the trained ANN Models. The R-Squared value between the observed and predicted values of RC is 0.9764 and EODV at peak DOD is 0.9840.

The observed and predicted values of RC and EODV at peak DOD from ANN models are shown in the Figures 5.24(a) and 5.24(b). Figures
5.25(a) and 5.25(b) show the comparison graph between the observed and predicted values of RC and EODV at peak DOD from ANN models. Figures 5.26(a) and 5.26(b) show the Bland Altman Plot for the same.

![Figure 5.24](image1.png)

**Figure 5.24** Observed and predicted values from ANN model (a) RC and (b) EODV at peak DOD at 20°C and 40°C Temperatures for GEO variable DOD cycling test.

![Figure 5.25](image2.png)

**Figure 5.25** Comparison graph between observed and predicted values from ANN model (a) RC and (b) EODV at peak DOD at 20°C and 40°C Temperatures for GEO variable DOD cycling test.
Figure 5.26  Bland Altman Plot between observed and predicted values from ANN model (a) RC and (b) EODV at peak DOD at 20°C and 40° C Temperatures for GEO variable DOD cycling test

5.3.5 ANFIS Model Description and Results for GEO Variable DOD Cycling

The ANFIS configuration to predict the RC for GEO variable DOD cycling has two inputs. The inputs are Temperature and cycle number. Each input is fuzzified with five Guassian membership function. The output is linear with five membership function to estimate RC. The number of rules is five. The network has been trained with error goal of 0.01. After successful training with 10 epochs the error goal achieved is 0.2621.

The ANFIS configuration to predict the EODV at peak DOD for GEO variable DOD cycling test has the two inputs namely Temperature and Cycle number. Each input is fuzzified with six guassian membership function. The output is linear with six membership function to estimate EODV at peak DOD. The number of rules is six. The network has been trained with error goal of 0.001. After successful training with 10 epochs the error goal achieved is 0.0058.
ANFIS structure for the Estimator model to find RC and EODV at peak DOD has been shown in the Figure 5.27(a) and 5.27(b) and the performance graph for the Estimator model to find RC and EODV at peak DOD are shown in Figure 5.28(a) and 5.28(b).

![ANFIS model Structure](image)

(a) ![Performance graph](image)

(b)

Figure 5.27 ANFIS model Structure for Estimator model (a) RC and (b) EODV at peak DOD for GEO variable DOD cycling test

![Performance graph](image)

(a) ![Performance graph](image)

(b)

Figure 5.28 Performance graph of ANFIS model (a) RC and (b) EODV at peak DOD for GEO variable DOD cycling test

Figure 5.29(a) and 5.29(b) show the observed and predicted values of RC and EODV at peak DOD from ANFIS model for GEO variable DOD cycling test. The comparison graph between the observed and predicted values of RC and EODV at peak DOD from ANFIS model is plotted in the Figure 5.30. The estimated R-squared value between the observed and predicted values of RC is 0.9970 and EODV at peak DOD is 0.9948. The
Bland Altman Plot between the observed and the predicted values of RC and EODV at peak DOD is given in the Figure 5.31(a) and 5.31(b).

![Bland Altman Plot](image)

(a) (b)

**Figure 5.29** Observed and predicted values from ANFIS model (a) RC and (b) EODV at peak DOD at 20°C and 40°C Temperatures for GEO variable DOD cycling test

![Comparison Graph](image)

(a) (b)

**Figure 5.30** Comparison graph between observed and predicted values from ANFIS model (a) RC and (b) EODV at peak DOD at 20° C and 40° C Temperatures for GEO variable DOD cycling test
Figure 5.31  Bland Altman Plot between observed and predicted values from ANFIS model (a) RC and (b) EODV at peak DOD at 20° C and 40° C Temperatures for GEO variable DOD cycling test

5.3.6  Comparison of Results and Discussion of Various Models Designed for GEO Variable DOD Cycling Test

Batteries are operated for two eclipse seasons in a year. Each season consist of 45 days with the total of 90 days in a year. In each season 23rd day will be the maximum eclipse duration and the DOD’s are also maximum. The RC measurement and the decrease in EODV have been measured for every 10th Peak DOD cycle representing 230 cycles. With this data pertaining to 1840 cycles is derived. In every peak DOD cycle the maximum DOD will be 60%. This experiment is accelerated test as explained in the earlier section. From the results the variable DOD cycle has been performed with two temperature settings of 20°C and 40°C to evaluate the capacity for each season for two upper and lower temperature settings in GEO space crafts.
It is observed from the results that the capacity degradation for initial 690 cycles is more compared with the remaining 1150 cycles. It can be seen from the Figure that at the worst possible temperature of 40°C the degradation at 690 cycles is 10% and for the remaining 1150 cycles the degradation is found to be 9%. The capacity degradation for variable DOD cycling increases with increase in temperature. From the observation of results for 20°C and 40°C, it is found that after 1840 cycles the degradations in capacity fading are 13% and 19% respectively.

The EODV at peak DOD for the high temperature the charge voltage is high with 3.6V and it decreases with increase in charge cycle. This is mainly due to the variation in internal resistance for the temperature of 40°C that is normally low compared to the internal resistance at temperature of 20°C. But the change in resistance will be more for higher temperatures and the change in resistance will be less for lower temperature. It is observed from the EODV graph of Figure 5.29(b) that the decrease in EODV is more for 40°C. The EODV below 3V is normally is considered to be failure of battery for any space mission. Below 3V the battery may not support the system.

The total of 18 patterns over 1840 cycles have been used for modeling the capacity fading due to variable DOD cycling. The results observed form the MR model clearly indicates both for RC and EODV the predicted values is lower than the observed value, then it increases again to decrease later, maintaining a linear curve. Both the predicted RC and EODV show the deviation is above ±1% for each of the values.
MVRPF model has shown a very close agreement for most of the values for RC and EODV and has very less variation for the temperatures over 1840 cycles.

Fuzzy model designed with the membership functions specified in Figure 5.20 is showing deviation for most of the values from the observed values and the deviation is maximum after 1380 cycles. This may be mainly due to human inference which defines the results.

ANN model output shows a small initial deviation and continuous agreement throughout the 1840 cycles in the prediction of both RC and EODV at peak DOD. It has a difference in variation of around ±2% for RC prediction and less than ±1% in EODV prediction. No extrapolation test has been conducted as 1840 cycles itself reflecting around 22 years of life of GEO space crafts.

The ANFIS predictions are plotted against the observed value in the Figure 5.29. It is observed from the graphs that ANFIS shows excellent prediction for both RC and EODV and the percentage difference is observed to be less than ±0.8% for both the predictions. It indicates the excellent prediction capability and generalizing capability of ANFIS compared with other models. The error value obtained from statistical and Bland Altman comparison is given in the Table 5.2. From the Figures it can be observed that ANFIS model confirms its superiority in the capability of accurate prediction reported in most of the literatures.
Table 5.2 Error values obtained from different models designed for GEO variable DOD cycling

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Model</th>
<th>R-squared value</th>
<th>Coefficient of Variation</th>
<th>Mean Square Value</th>
<th>Ave Abs Pet Error</th>
<th>Bland Altman Plot</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>RC EODV</td>
<td>RC EODV</td>
<td>RC EODV</td>
<td>RC EODV</td>
<td>RC EODV</td>
</tr>
<tr>
<td>1</td>
<td>MR</td>
<td>0.9119 0.9639</td>
<td>0.0168 0.0058</td>
<td>2.2809 0.0004</td>
<td>1.196 0.457</td>
<td>-2% to +4%</td>
</tr>
<tr>
<td>2</td>
<td>MVRPF</td>
<td>0.9886 0.9854</td>
<td>0.0062 0.0041</td>
<td>0.3166 0.0002</td>
<td>0.445 0.305</td>
<td>-1.5% to +1.5%</td>
</tr>
<tr>
<td>3</td>
<td>Fuzzy</td>
<td>0.9535 0.9262</td>
<td>0.0105 0.0073</td>
<td>0.9031 0.0006</td>
<td>0.722 0.574</td>
<td>-3% to +3%</td>
</tr>
<tr>
<td>4</td>
<td>ANN</td>
<td>0.9764 0.9840</td>
<td>0.0091 0.0041</td>
<td>0.6648 0.0009</td>
<td>0.700 0.328</td>
<td>-1.5% to +2%</td>
</tr>
<tr>
<td>5</td>
<td>ANFIS</td>
<td>0.9970 0.9948</td>
<td>0.0032 0.0023</td>
<td>0.0843 0.0001</td>
<td>0.229 0.180</td>
<td>-0.6% to +0.8%</td>
</tr>
</tbody>
</table>
5.4 CONCLUSION

The experimental results and the models using different techniques such statistical, Fuzzy, AI are presented and discussed in this chapter for prediction of RC during storage/ calendar period and the effect of temperature, variable DOD over charge /discharge cycle on RC and EODV at peak DOD.

The experiment results are conducted for seven and half years to find the RC / capacity fading in storage period during solstice with various temperature and state of charge and results are presented. The results are used in modeling. The model results indicate that the capacity fading is nonlinear function in variation with temperature and SOC. MR model results clearly indicates this. It also indicates that the effect of SOC influences the capacity fading more compared to the temperature from the estimated model equation. Comparing the results from the Fuzzy, ANN, ANFIS models, it can be seen that all the models show excellent agreement between the observed and predicted values. The extrapolation results from ANN model trained with four year to estimate the RC for seven and half years shows better result till sixth year and it starts deviating beyond that. The extrapolation results are encouraging with limitation in reliability for the results beyond six years.

The experimental result and the designed models in estimation of RC and EODV at peak DOD with variable DOD cycling for temperatures of 20°C and 40°C are presented in this chapter. Comparison of the results from the different models shows that ANN and ANFIS models are better than the other models. Among these models ANFIS model shows excellent interpolation capability with variation between the observed and predicted values well bellow ±1% for both RC and EODV at peak DOD.