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Charging Time Reduction Using Optimized Multistage Constant Current Charging Pattern for Lithium Ion Batteries

Fahad Ur Rehman[1], Tahir Mehmood[2] and Muhammad Bilal Iqbal[3]
[1]Electrical Engineering Department University of Engineering and Technology Taxila 75270- Pakistan.
[2]Electrical Engineering Department University of Engineering and Technology Taxila 75270- Pakistan.
[3]GCT Taxila and Former Research Scholar at Electrical Engineering Department University of Engineering and Technology Taxila 75270- Pakistan.
[1]fahadcust@yahoo.com [2]tahir.mehmood@uettaxila.edu.pk [3]bilal.mbi87@gmail.com

ABSTRACT

In this research paper a technique is proposed combining Salps Swarm Algorithm (SSA) and response surface methodology to optimize multistage constant current charging pattern for Lithium Ion battery. The optimization aims to maximize the charging cost-benefit function to get charging time reduction at higher performance rate. A searching strategy is based on Response surface method RSM and SSA with Fuzzy Deduce Fitness Evaluator (FDFE) to maximize charging cost-benefit function. The objective is to maximize the cost effective function based on non linear weightings' Charging Time CT and Normalize Discharge Capacity NDC used in the objective function. Fuzzy logic is acclimated to convert S/N ratio of quality characteristics CT , NDC derived from RSM into a single output using FDFE to maximize cost-benefit function. Standard CCD design of RSM is used to perform experiments. Proposed technique is verified experimentally by using multichannel programmable battery tester/charger (NEWARE) 5V, 5A. The comparison with CC-CV charging method and PSO optimized pattern proves superiority of multistage CC technique. Verification experiment proves 19% charging time reduction, 0.9% charging efficiency improvement and 5% life cycle increment.

Keywords: *Constant current, constant voltage, Response surface methodology, Fuzzy deduces fitness evaluator, Normalized discharge capacity, Multilevel charging.*

1. INTRODUCTION

Rechargeable batteries have most important role in energy storage solution. They have a vital role in portable electronics, electric vehicles, smart grids, renewable energy applications and many other applications. Different type of rechargeable battery technologies is available with different chemistries. Lead acid batteries and Lithium ion are most of the commonly used technologies. But among all available battery technologies Li-Ion batteries are best choice in newly invented electronic appliances. Their attractive characteristics such as, high terminal voltage, high specific power and energy, immunization of memory effect and self discharge make it attractive choice for energy storage solution.

Fast charging always remains an important issue for researchers in battery development technology. High charging rate results life degradation, increase in internal resistance and damage the separator layer due to thermal runaway of battery. Conventional Constant-Current Constant-Voltage (CC-CV) method is inapplicable for fast charging because its C-V charging phase results more charging time and less charging efficiency.

To handle these problem researchers proposed different techniques and charger design. A built in resistance technique (BRC) to decrease CT of Li-Ion battery is proposed in [1]. Digital control technique to achieve constant current constant voltage without current feedback is proposed in [2]. Reference [3] addresses different charging techniques including CC-CV, pulse charging, five stage charging and boost charging technique. These techniques improves the performance of batteries life cycle and decrease charging time, among these aforementioned techniques multilevel charging [5] proves less chemical stress and charging time.

Electrochemical behavior of battery is responsible to obtained charging pattern which is not best solution forever. In recent years different intelligent control algorithms like fuzzy, neural networks and GA are embedded in microcontrollers to enhance the performance of the charger, in order to improve prediction, operating performance and accuracy of charger. Although these intelligent algorithm improve the charger performance but accurate battery model under charge is required for algorithms. However a authentic battery model of Li-ion battery is arduous to obtain due to its varying electro-chemical properties.

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Therefore only improving the charging mode of the charger isn't best solution of fast charging and battery life is an aspect of battery performance depending upon charging method.

In this paper, SSA and RSM are applied to find optimal five stage charging pattern for fast charging of lithium ion battery. First the analytical expression was developed between input levels of current and fitness function. Then obtained second order equation is manipulated as fitness function of the SSA and a maximum of the function is considered as finding object for the SSA algorithm. Finally obtained results are verified on Neware battery tester BTS 4000 (5 volt 5A) using 2600mAh Li-ion rechargeable battery cells.

2. PROBLEM FORMULATION

Mathematical modeling of Li-ion battery is not possible yet due to its complex chemical characteristics. So it is difficult to obtain optimal charging level for every charging stage using battery model. So it's not possible to find optimal charging levels for all charging stages using battery model. In addition Li-ion battery life depends on charging time, charging stages, internal resistance and overheating. In this work best five stage charging pattern for fast charging is achieved to meet best charging cost benefit. Therefore the objective function for five stage pattern is formulated as

Maximize

$$f_{ce}^{i}(T_{ch}^{i}(I_j^i), C_{dis-norm}^{i}(I_{dis}^{i})) = f_{\alpha}^{i}(T_{ch}^{i})T_{ch}^{i}(I_j^i) + f_{\beta}^{i}(C_{dis-norm}^{i})C_{dis-norm}^{i}(I_{dis}^{i}), \qquad I_j^i \in \$$$

Where $I_j^i = [I_1^i, I_2^i, I_3^i, I_4^i, I_5^i]$

Subjected to

$$30min \geq T_{ch}^{i}(I_j^i) \leq 90min$$

$$80\% \geq C_{dis-norm}^{i}(I_{dis}^{i}) \leq 100\%$$

$$I_j^i \geq I_m^i \quad If \quad j < m, \quad j, m = 1,2,3 \dots \dots ,5$$

Where $ is for all possible feasible multistage charging pattern. Two performance indexes charging time (CT) and normalize-discharge-capacity (NDC) are taken in cost-benefit function. f_{α}^{i} And f_{β}^{i} are the coefficients or weighting of CT and NDC to stress their contribution in cost benefit function. NDC is defined as the percentage of the ratio of discharge capacity when battery charges through multistage CC ($C_{dis-5\,stage}^{i}$) to the CC-CV ($C_{dis-CCCV}^{i}$) technique, both with the same discharge rate (.1C) to appraise battery capacity. In **Fig. 1** Fuzzy deduced fitness-evaluator is used in this work and most appropriate regulating rules of weighting factors are formulated by fuzzy logic. From **Fig. 2 (a, b, c)** (CT) and (NDC) was used as input parameters and output F^i is value of effective function. The mamdani-type-inferential method with center-of-area (COA) defuzzification procedure was used for crisp controller output. In addition UOD in the member functions of variables, T_{Ch}^{i} and $C_{norm-dis}^{i}$ is defined in the domain [30, 90] and [80%, 100%] respectively. UOD is the output is depict in the domain of [0, 1].

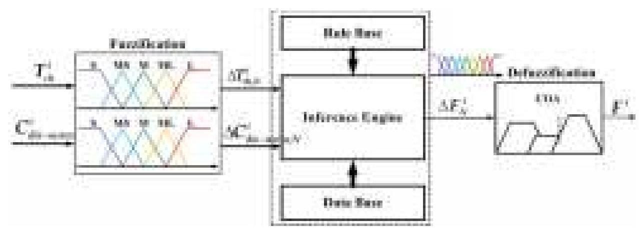
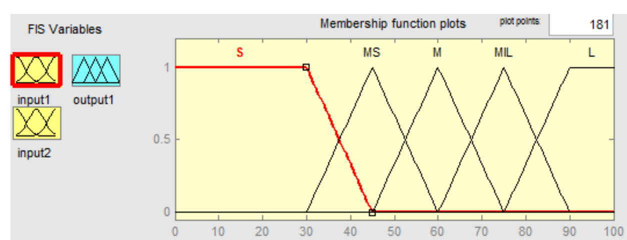


Figure 1. Scheme of FDFE



(a)

(b)

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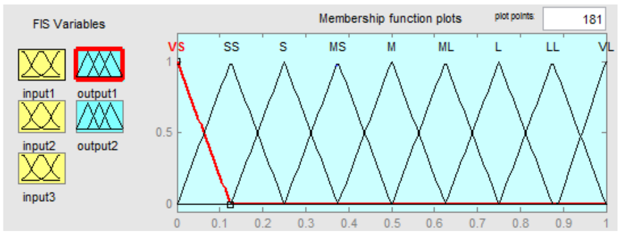

Figure2. Member functions of input variables

Rules are defined on the perception that if charging time is small and normalized discharge capacity is large then output should be large, smaller NDC and larger CT results in small output value of function. Table 1 shows the defined rules to obtain the optimize value of objective function.

Table 1 Rule based derivation for fitness function

NDC\ CT	S	MS	M	ML	L
S	M	ML	L	LL	VL
MS	MS	M	ML	L	LL
M	S	MS	M	ML	L
ML	SS	S	MS	M	ML
L	VS	SS	S	MS	M

3. OPTIMIZATION METHOD

3.1. RSM

Response surface methodology is used to optimize output response having multiple independent factors on which output response depends. Response surface methodology is the combination of statistical and mathematical techniques to find optimal solution. In this technique mathematical and statistical process are used to create an adequate relation between input variables x1, x2, x3,……,X_k and output response y. such a relation is uncomprehended but could be found by a low degree polynomial model of the form

Y= f′(x)β + ϵ

Second order model used to fit data of experiments (DOE) obtained from series of experiment is in Eq. 2.5.

$$Y=\beta_0+\sum_{1=1}^{k}\beta_i X_i+\sum_{i=1}^{k}\beta_{ii} X_{ii}+\varepsilon \qquad (2.5)$$

Least square method is applied to obtain the coefficient vector β. β regression coefficient could be obtained from the following relation.

$$\hat{\beta} = (X'X)'X'Y \qquad (2.6)$$

$$Y' = X\hat{\beta}$$

(2.7) R^2_{adj} coefficient of adjustment, which was determined by the determination coefficientR^2, could be used to check the fitness of the model. When its value is close to 1 its mean the model is fitted accurately.

$$R^2_{adj} = 1 - \frac{S_{se}(n-m-1)}{S_{st}(n-1)} \qquad (8)$$

$$S_{se} = \sum_{i=1}^{n}\left(Y_i - \widehat{Y}_i\right)^2 \qquad (9)$$

$$S_{st} = \sum_{i=1}^{n}(Y^i - Y')^2 \qquad (10)$$

S_{st} and S_{se} are the sum of squares of total deviations and residuals respectively. m is the number of variables and n is number of sampling points, $\widehat{Y}_i$ is estimated value Y_i is actual value and $\acute{Y}$ is average value.

3.2 Central Composite Design

Central composite design is use to enable regression parameters fit into a second order model. CCD is widely used DOE in response optimization, each factor is tested in there level -1, 0, 1 which are called coded units. CCD requires three types of experimental point's 2^k factorial points, 2k axial experiments and n number of center point experiments. To determine the relation between coded units and absolute values following equation is used. In this paper CCD with 16 factorial points, 10 axial points and 6 center points is used to perform experiments. Table 2 show the level setting of the input currents for each stage.

Table 2 Experimental design current levels and settings

Currents\Levels	I1(c)	I2(c)	I3(c)	I4(c)	I5(c)
High level 1	1.5	1.25	1.0	0.75	0.5

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Medium level **0**	1.4	1.15	0.9	0.65	0.4
Low level **-1**	1.3	1.05	0.8	0.55	0.3

3.3. SSA Algorithm

Salps have a transparent barrel-shaped body and similar to Salpidae family. They just like to the jelly fish and their movement is also just like jelly fish. Thrilling attitude of the salps is their swarming behavior for food search. In deep sea level salps make a group called salp chain.

For the mathematical modeling of the salp chain, chain is first separate into two groups Leaders and followers. Leaders are the first half part of the swarm and followers follow them gradually.

As like another techniques, position of salps is described in n dimensional search space, n is the number of input variables. Two dimensional matrix called x is used to load position of salps. There is a diet source F in the search space as a target for salps. To amend the position of leading salps Eq. 2.1 is used

$$x_j^1 = \{F_j + c_1((ub_j - lb_j)c_2 + lb_j) \quad c_3 \geq 0 \qquad (2.1)\text{ (a)}$$

$$x_j^1 = \{F_j + c_1((ub_j + lb_j)c_2 + lb_j) \quad c_3 < 0 \qquad (2.1)\text{(b)}$$

x_j^1 is the position of first salp in J-th dimention, F_j is food source ub_j and lb_j represent upper bound and lower bound limits, c_1, c_2 and c_3 are the random values. Equation 2.1 shows that leaders only update there position according to food source. C_1 is considered as most important coefficient because it controls the exploration and exploitation in SSA, only leading salps change their position according to c_1. Eq 2.2 shows that with number of iteration c_1 decreases gradually so it moves swarm from exploration to exploitation.

$$C_1 = 2e^{-\left(\frac{4l}{L}\right)^2} \qquad (2.2)$$

Where L is maximum iteration I is current iteration. C-2 and c-3 are random numbers generated steadily in between [0, 1], they decide that in j_th dimension position will be towards positive infinity or negative infinity. To amend position of the followers (2.3) is utilized.

$$x_j^i = \frac{1}{2}(x_j^i + x_j^{i-1}) \qquad (2.3)$$

Where $i \geq 2$ and x_j^i shows position of ith follower in jth dimension.

4. SEARCHING PROCEDURE OF OPTIMAL CHARGING PATTERN

Searching flow chart of the suggested technique is given in figure 3, each step of the given system is described as follows.

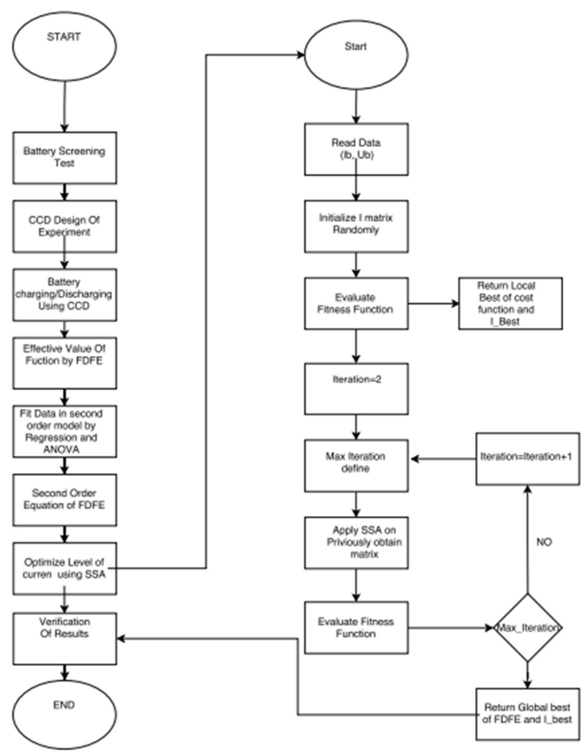

Figure3. Flow chart of proposed algorithm

Step 1) Battery screening test: the specification of used Li-on battery are nominal voltage of 3.7 volt and rated capacity of 2600mAh. First battery impedance test conducted to check battery reliability and performance.

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For this purpose 60 new batteries were test and 16 were selected for experiments.

Step 2) Design of Experiments: As we have 5(I1-I5) input charging parameters, values of each level of current control the charging time and value of cost function. Face centered CCD chosen for experimental design having 16 factorial points, 10 axial points and six center points.

Step 3) Charging/discharging batteries: charging process was managed by using Neware battery tester BTS 4000 5 volt 6 amp. After discharging with same equipment we get tow variable of each experiment CT and NDC. These two variables are used in FDFE to find value of cost function.

Step 4) ANOVA: after fitting data into second order model analysis of variance is used to check the importance of each current level and model validity. The analysis was conducted for level of confidence not less than 95% mean p value should be greater than 0.05.

Step 5) Second order Model Equation: after confirmation of model validity we have second order model equation of our problem. Second order equation of a problem could be used in SSA algorithm to optimize the input variable at the maximum output.

Step 6) SSA algorithm: MATLAB is used to implement SSA algorithm to find optimum solution of the second order equation. SSA is fast converging algorithm and easy to implement.

Step 7) Confirmation tests: after having optimized pattern for each stage of current confirmation tests are performed using Neware battery tester BTS 4000.

According to the levels of each current, by mean of the software MINITAB CCD is built in **Table 2**. Based on design output of each experimental setup is given in **Table 4**, MINITAB software is used to create response surface analysis.

TABLE 4 CCD DESIGN AND OUTPUT VALUE OF FDFE

Sr	I1	I2	I3	I4	I5	FDFE
1	-1	-1	-1	-1	1	62.27
2	1	-1	-1	-1	-1	60.12
3	-1	1	-1	-1	-1	63.27
4	1	1	-1	-1	1	62.15
5	-1	-1	1	-1	-1	63.28
6	1	-1	1	-1	1	60.19
7	-1	1	1	-1	1	62.87
8	1	1	1	-1	-1	62.75
9	-1	-1	-1	1	-1	62.23
10	1	-1	-1	1	1	62.17
11	-1	1	-1	1	1	60.18
12	1	1	-1	1	-1	62.18
13	-1	-1	1	1	1	59.90
14	1	-1	1	1	-1	62.80
15	-1	1	1	1	-1	60.17
16	1	1	1	1	1	61.37
17	-1	0	0	0	0	59.87
18	1	0	0	0	0	61.90
19	0	-1	0	0	0	60.25
20	0	1	0	0	0	60.38
21	0	0	-1	0	0	59.80
22	0	0	1	0	0	63.25
23	0	0	0	-1	0	62.00
24	0	0	0	1	0	62.25
25	0	0	0	0	-1	59.00
26	0	0	0	0	1	59.25
27	0	0	0	0	0	63.45
28	0	0	0	0	0	63.15
29	0	0	0	0	0	60.17
30	0	0	0	0	0	59.35
31	0	0	0	0	0	61.90
32	0	0	0	0	0	62.15

ANOVA:

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Analysis of variance is carried out using MINITAB software **Table 4** shows greater F value of model and P-Value of 0.001 which is less than 0.05, indicating the model validity. In model summary **Table 5** S value is less than 1 and R^2 = 95.15 also confirm the model fitness. All the terms shown in table are significant terms non significant term are removed by the analysis in software.

TABLE 5 ANOVA Table

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	11	57.7581	5.2507	35.86	0.001
Linear	5	41.4765	8.2953	56.65	0.002
I1	1	16.5313	16.5313	112.90	0.000
I2	1	10.9044	10.9044	74.47	0.003
I3	1	4.8776	4.8776	33.31	0.002
I4	1	5.9628	5.9628	40.72	0.001
I5	1	3.2004	3.2004	21.86	0.000
Square	2	11.2476	5.6238	38.41	0.004
I2*I2	1	8.3749	8.3749	57.19	0.002
I5*I5	1	1.0616	1.0616	7.25	0.002
2 way interaction	4	5.0341	1.2585	8.59	0.000
I1*I2	1	0.6561	0.6561	4.48	0.047
I3*I4	1	1.8360	1.8360	12.54	0.002
I3*I5	1	1.6770	1.6770	11.45	0.003
I4*I5	1	0.8649	0.8649	5.91	0.025
Error	20	2.9286	0.1464		
Lack of Fit	15	2.8806	0.1920	20.03	0.002
Pure Error	5	0.0479	0.0096		
Total	31	60.6867			

Model summery

S	R_sq	R_sq(adj)	R_sq(pred)
0.38266	95.17%	95.52%	95.87

5. MATHEMATICAL MODEL

Equation between cost function and input currents have been find out by RSM shown as follows:

$$FDFE = 61.999 - 0.9583I_1 - 0.7783I_2 - 0.5206I_3 - 0.5756I_4 - 0.4217I_5 - 1.549I_2^2 + 0.551I_5^2 - 0.2025I_1I_2 + 0.3388I_3I_4 + 0.3238I_3I_5 + 0.2325I_4I_5$$

SSA implies directly on the above model equation, model maximum value is preferred as finding object. MATLAB is used to dissect fitness value of the function. According to the results from SSA algorithm maximum value of the cost function was 65.095 at the optimized current levels. Convergence curve of SSA algorithm is given in **Figure 4**.

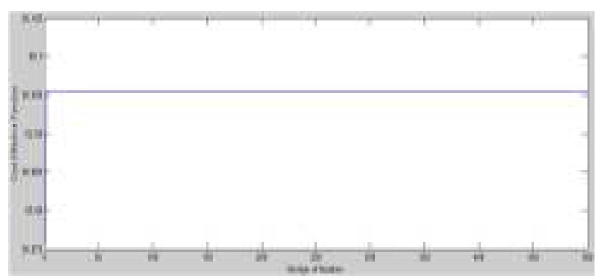

Figure4. Convergence curve of SSA algorithm

6. RESULTS

From SSA algorithm the optimize level of currents are given in table 5.

Table 6 Coded and uncoded values of optimized current

Currents\Stages	I1	I2	I3	I4	I5

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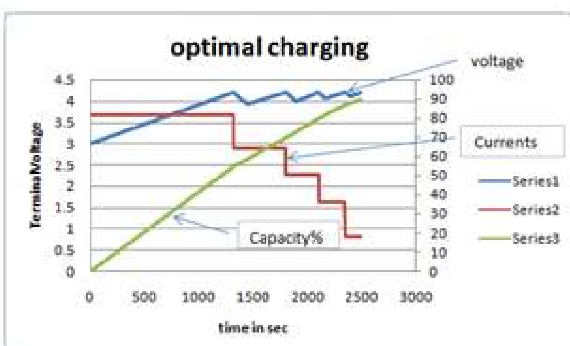
Coded Values	-0.036	0.2041	-0.402	0.8993	-0.4301
Values in C rate	1.416	1.117	0.8807	0.631	0.316
Absolute Values (amp)	3.68	2.90	2.289	1.64	0.82

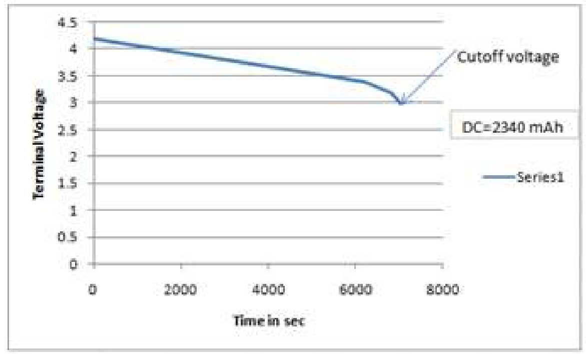
Relation between coded values and real values is given by following Eq. (11)

$$X = b.\ coded\ value + a \qquad (11)$$

Confirmation test is per formed using Neware Battery tester and resulted waveform is shown in figure 4 (a). According to waveform battery is charged in 40.5 min reaching at charging capacity of 90% almost. From figure it is shown that when a battery limit voltage reaches at V-limt the next phase of current is given by the tester and till the last stage reaches at which battery is charged upto 90% of its capacity. Figure 4 (b) gives the discharging curve of the battery. A battery is discharged with 0.5C discharge rate and completely discharge in 1.81 hours.



(a)



(b)

Proposed Algorithm	Charging Time (min) 40.5 Charged Capacity (mAh) 2366 Discharge Capacity (mAh) 2341 Charge Efficiency (%) 98.9%	CT improvement $=\frac{(42-40.5)}{42}\times$ 100=19% Charging η% = (0.9 − 0.4)= 0.5%
PSO Optimization Method	Charging Time (min) 42 Charged Capacity (mAh) 2578.5 Discharge Capacity (mAh) 2537.2 Charge Efficiency (%) 98.4%	

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7 CONCLUSION

This paper introduces a new optimization method which associates RSM and SSA to optimize cost effective function for multilevel charging Pattern of Li-Ion battery. During optimization process several techniques have been embrace, such as CCD for experimental design, RSM for fitness function and SSA for optimization of cost function and Neware battery tester for experiments. As a result maximum value of FDFE has been obtained for optimal setting of CC charging pattern. Verification experiments shows charging time reduction of 19%, 0.5% charging efficiency improvement and 5% life cycle increment of Li-ion battery.

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AUTHOR PROFILES

Fahad Ur Rehman received degree in Electrical computer engineering from CIIT Islamabad Pakistn in 2013. Currently he is a research student of Msc Electrical (power) at Uet Taxila Pakistan.

Tahir Mehmood received Bsc, Msc and Phd in Electrical Engineering from Uet Taxila Pakistan. currently he is Professor in Electrical department of Uet Taxila Pakistan.

Mohammad Bilal Iqbal received Bsc Electrical from Federal Urdu University Pakistan and Msc Electrical Engineering from Uet Taxila Pakistan. Currently he is Instructor Electrical in GCT Taxila Pakistan.