❏     512

# Determination of Volume of Capacitor Bank for Static VAR Compensator

**Md. Ruhul Amin, Rajib Baran Roy**
Department of Electrical and Electronic Engineering, University of Information Technology and Sciences (UITS),
Dhaka-1212, Bangladesh

| Article Info | ABSTRACT |
|---|---|
| | In high voltage AC system, the system voltage and frequency change rapidly with the variation of load. The reactive power also changes with the variation of load which affects the system voltage therefore it is necessary to analyze the power system in order to determine system parameters and its variation under various load conditions. The capacitor bank size is determined by calculating existing reactive power and required reactive power in system for Static VAR Compensator (SVC) is focused in this paper. Base case load flow is used to analysis power system. After identifying low voltage buses, arbitrary caciptor back is imposed in bueses and results are checked whether it is met or not in the system demand level. Here MATLAB coding is used to find the low voltage affected bus and automated calculation of capacitor back size is done by MATLAB also. The proposed method of identification of low voltage buses and determination of capacitor bank are faster and easier than the conventional method.<br><br> |

*Corresponding Author:*

Md. Ruhul Amin
Department of Electrical and Electronic Engineering,
University of Information Technology and Sciences (UITS),
GA - 37/1, Pragati Sharani, Gulshan-2, Dhaka-1212, Bangladesh.
Email: ruhul.amin@uits.edu.bd

## 1.     INTRODUCTION

In an electric power system, which is AC (alternating current) by nature for the most advantages, the equipments and other industrial inductive loads draw reactive power. The increasing demand of reactive power does really have its own major impact on the generating units, lines, circuit breakers, transformers, relays and isolators. More reactive power demand results in increasing dimensions and cost which reduce the whole power system efficiency [1]. In distribution systems, the voltage at the load end tends to get lower due to the lack of reactive power [2]. But if the total reactive load is feed only by the generation unit, it will lower the maximum real power capacity of generator. Moreover the additional current flow associated with reactive power can cause increased losses and excessive voltage sags. In such cases, local VAR support is offered using shunt capacitors; this is called reactive power compensation. The most common method for this compensation is to add capacitor banks to the system [3]. Capacitors are attractive because they are economical and easy to maintain. Not only that, they have no moving parts, unlike some other devices used for the same purpose. Using shunt capacitors to supply the leading currents required by the load relieves the generator from supplying that part of the inductive current. The system benefits due to the application of shunt capacitors include [4] reactive power support, voltage profile improvements, line and transformer loss reductions, release of power system capacity and savings due to reduced energy loss. These benefits apply for both distribution and transmission systems. Maintaining a constant standard voltage is very important for most of the industries and home appliances. Low voltage profile may cause power losses in the system, low performance in the appliances and industrial machineries. Sometimes it may cause severe damage to the

appliances and loss in productions. These problems can be eliminated by using SVC with capacitor banks [5]. To attain a certain voltage level, determination of the size of these capacitor banks is necessary.

A method is proposed to determine capacitor bank size in this work. The fast decoupled method [6] is used for analyzing the power flow of 42 buses and later MATLAB coding is used for determining the buses having problem in reference system voltage. The proposed decoupled method of is faster and easier than the conventional method also.

## 2.    CONCEPT OF DETERMINATION OF CAPACITOR VOLUME

Presently the size of capacitor bank needed for attaining a satisfactory voltage level is determined in a tedious way. From a base case load flow the voltage scenario of the entire power system is obtained. Buses suffering from low voltage are marked. First an arbitrary size of capacitor bank is assumed at one of the candidate buses. A load-flow is done considering that shunt capacitor to check the improvement of voltage of that bus. If it is not satisfactory, the capacitor bank size is changed (increased or decreased) correspondingly and again another load flow is done. To find the actual capacitor bank size, load-flow is needed to be run several times until the desired voltage level (0.95 per unit (p.u.) or 1.0 p.u.) is achieved. Then this process of repeated load-flow is applied to find the required capacitor bank size at other candidate buses one by one.

## 3.    LOAD FLOW TECHNIQUES

Load flows can be performed using different techniques. Those are Gauss-Seidel method, Newton-Raphson method and Fast Decoupled method. The last one is the most popular method. To calibrate the proposed method, here Fast Decoupled method has been chosen as it is the fastest of all the conventional methods. Algorithm for performing load flow in fast decoupled method is explained here. Prior to that, algorithm for constructing the $Y_{bus}$ matrix is briefly explained as it is a pre-requisite for any load-flow.

### 3.1.  Finding Bus Admittance Matrix ($Y_{bus}$ Matrix)

Steps in constructing the $Y_{bus}$ by inspection [7]

The $Y_{bus}$ is symmetric. $Y_{ij}=Y_{ji}$

$Y_{ii,}$ the self-admittance (diagonal element), is equal to the sum of the primitive admittances of all the components connected to the ith node.

$Y_{ij,}$ the ijth element of the $Y_{bus}$ (off diagonal element), is equal to the negative of the primitive admittance of all components connected between nodes i and j. It is to be noted that if more than one component is connected in parallel between two nodes, equivalent primitive admittance of the components is first obtained before determining the entry in the $Y_{bus}$.

### 3.2.  Fast Decoupled Method

The algorithm for Fast Decoupled Method [6]-[10] is described below.

**Step 1.**  Formulate and Assemble $Y_{bus}$ in Per Unit.

**Step 2.**  Make necessary initial assumptions for voltage magnitude and phase angles, for load (PQ) buses take
$1 \angle 0^{o}$ and for generator (PV) bus take $1.02 \angle 0^{o}$

**Step 3.**  Calculate real powers of all the buses with assumed data from the following equation.

$$P_i = \left|V_i\right|^2 G_{ii} + \sum_{n=1,n\neq i}^{N} \left|V_i V_n Y_{in}\right| \cos(\theta_{in} + \delta_n - \delta_i)$$

Calculate initial real power mismatch vector $\left[\dfrac{\Delta P}{|V|}\right]$ from the given data (real power) and calculated real power.

**Step 4.**  Generate the '$\overline{B}$' matrix taking negative of the susceptances of $Y_{bus}$. It will be used as constant Jacobian Matrix for the rest of the calculations.

**Step 5.**  Compute the correction vector of phase angles $\left[\Delta\delta\right]$ by multiplying the inverse of the 'B' matrix by real power mismatch vector

$$as,\left[\overline{B}\right].\left[\Delta\delta\right]=\left[\frac{\Delta P}{|V|}\right]$$

$$\Rightarrow\left[\Delta\delta\right]=\left[\overline{B}\right]^{-1}.\left[\frac{\Delta P}{|V|}\right]$$

**Step 6.** Update the phase angles. $\delta_{(1)}=\delta_{(0)}+\Delta\delta_{(0)}$

**Step 7.** Calculate reactive powers of only the load buses.

$$Q_i=-\left|V_i\right|^2 B_{ii}-\sum_{n=1,n\neq i}^{N}\left|V_i V_n Y_{in}\right|\sin(\theta_{in}+\delta_n-\delta_i)$$

Calculate initial reactive power mismatch vector $\left[\dfrac{\Delta Q}{|V|}\right]$

**Step 8.** Compute the correction vector of phase angles $\left[\Delta|V|\right]$ by multiplying the inverse of the 'B' matrix by real power mismatch vector.

$$as,\left[\overline{B}^*\right].\left[\Delta|V|\right]=\left[\frac{\Delta P}{|V|}\right]$$

$$\Rightarrow\left[\Delta|V|\right]=\left[\overline{B}^*\right]^{-1}.\left[\frac{\Delta P}{|V|}\right]$$

**Step 9.** Update the voltage magnitudes. $V_{(1)}=V_{(0)}+\Delta\left|V\right|_{(0)}$ .This is done only for the load buses.

**Step 10.** Return to step 3, repeat the procedures until all mismatches are within the specified tolerance.

### 3.3. Traditional Method for Computing Capacitor Bank Size

The algorithm for determining the size of capacitor bank by traditional method is described below [11]-[12].
1. Form $Y_{bus}$ matrix of the network.
2. Perform base case load flow by the given network data.
3. Mark the buses suffering from low voltages having voltages under 0.95 p.u.
4. Select a candidate bus K and choose a size for shunt capacitor bank for the bus.
5. Perform another load flow and observe the bus voltage $V_K$.
6. Calculate absolute error from the target voltage, $|V_K-V_{desired}|$ and check whether the error is less than a fixed tolerance level (such as 0.001).
7. If the error is greater than the tolerance, check whether the attained voltage is below or over the desired voltage.
8. If the voltage is still below the desired voltage, then more VAR is needed. So increase the value of capacitor bank and GO TO step 5.
9. If the voltage is above the desired voltage, then decrease the value of capacitor bank and GO TO step 5.
10. In step 6, if the bus voltage absolute error is less than the tolerance, save the capacitor bank size.
11. Check whether the sizes of capacitor banks for all the candidate buses are determined or not. If not, then GO TO step 4.
12. End.

### 4. PROPOSED METHOD

Let a simple circuit [8] with an AC voltage source, a resistor, an inductor and load be considered in figure 1. The corresponding phasor diagram of voltage & current of the circuit is shown in fig 2.
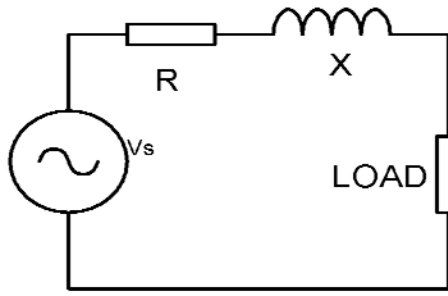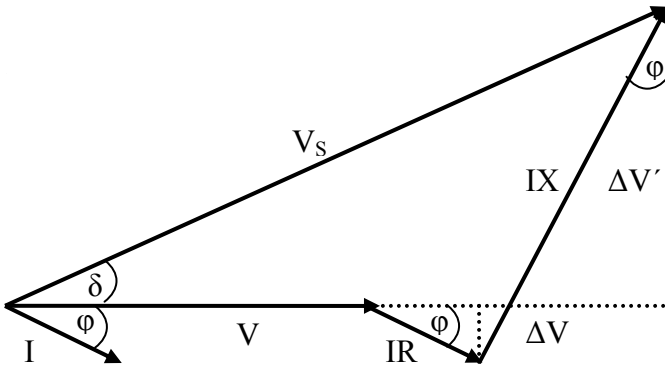
Figure 1. A simple AC series circuit          Figure 2. Phasor diagram of the simple AC series circuit

From the figure 2, it can be written,

$$V_s{}^2 = \left(V + \Delta V\right)^2 + \Delta V'^2 \tag{1}$$

Where the $\Delta V = IR \cos\phi + IX \sin\phi = \dfrac{RP}{V} + \dfrac{XQ}{V}$

And $\Delta V' = IX \cos\phi - IX \sin\phi = \dfrac{XP}{V} - \dfrac{RQ}{V}$

Practically, $V + \Delta V \gg \Delta V'$ so neglecting $\Delta V'$, equation (1) can be written as

$V_s = V + \Delta V = V + \dfrac{RP}{V} + \dfrac{XQ}{V}$

Hence the reactive power is given by

$$Q = \frac{V_s V - V^2 - PR}{X} \tag{2}$$

Differentiating equation no (2) with respect to V, we get

$$\frac{\delta Q}{\delta V} = \frac{V_S - 2V}{X} \tag{3}$$

For a three phase short circuit at the receiving end (V=0)

$$\frac{\delta Q}{\delta V} = \frac{V_S}{X} = I_{SC} \tag{4}$$

The rate of change of reactive power with respect to voltage at a node is equal to the short circuit current. However in a system with many buses the short circuit current [5] at any bus K is obtained neglecting pre-fault current (i.e. no load) as follows

$$I_{sc,K} = \frac{V_{f,K}}{Z_{KK}} \tag{5}$$

Where $V_{f,K}$ = Pre-fault voltage t bus K which is usually considered as 1 p.u.
$Z_{KK}$ = Diagonal element corresponding to bus K in the system bus impedance matrix $Z_{bus}$.
So equation (2 and 4) can be extended to any bus K in large system as follows.

$$\frac{\delta Q}{\delta V} = I_{sc} = \frac{1}{Z_{KK}} \tag{6}$$

So VAR required at a bus in respect to the change in its voltage $\Delta V$ can always be obtained as

$$\Delta Q_K = \frac{1}{Z_{KK}} \Delta V_K \tag{7}$$

$$\text{i.e. } Q_{K,reqd.} - Q_{K,existing} = \frac{1}{Z_{KK}} (V_{K,reqd.} - V_{existing}) \tag{8}$$

### 4.1. Algorithm and Flow Chart of Proposed Method of Computation
1. Form $Y_{bus}$ matrix of the network.
2. Find $Z_{bus}$ matrix of the network inverting the $Y_{bus}$ matrix. $Z_{bus} = Y_{bus}^{-1}$.
3. Perform base case load flow by the given network data.
4. Identify K buses suffering from low voltages having voltages under 0.95 p.u.
5. Select a candidate bus K and find the desired voltage raise, $\Delta V_K$.

$$\Delta V_K = V_{K,reqd.} - V_K$$

6. Find the required VAR size.

$$\Delta Q_K = \frac{1}{Z_{KK}} \Delta V_K$$

Where, $Z_{KK}$ = Corresponding diagonal element of $Z_{bus}$ for the candidate bus K.

$$\Delta Q_K = Q_{K,reqd.} - Q_{K,existing}$$

7. Run a test load-flow using a capacitor bank, $\Delta Q_K$ MVAR at the bus K and find new $V_K$.
8. Repeat steps 5, 6 and 7 for other buses mentioned in step 4.
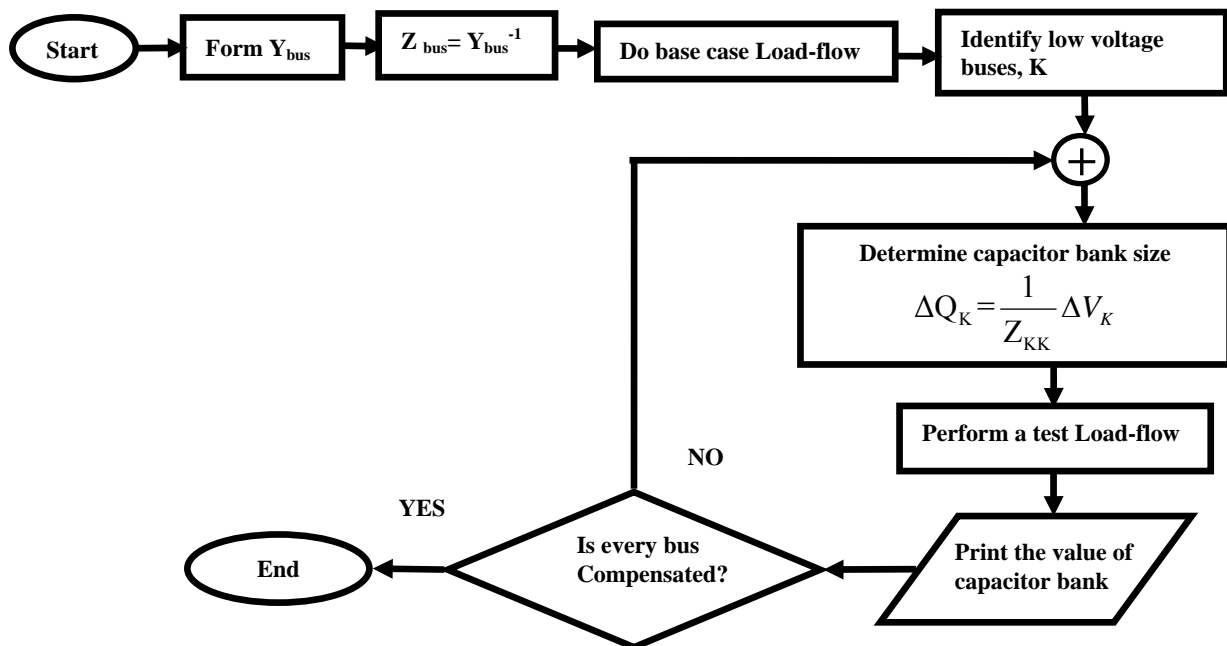


Figure 3. Flow chart of proposed method of computation

## 5.    RESULTS AND DISCUSSION
In the previous chapter, a method has been proposed for reactive power compensation to improve the voltage profile of a power system. In this chapter, to verify the validity of the method, it is applied on various practical power system networks.

### 5.1. System Network
The network used here is a very simple four bus network consisting two generator-bus and two load-bus with no transformer connected to any of the buses. Here bus no 1 named Birch is the slack-bus. The capacity of generator connected at bus 4 is 318MW. All the four buses supplies some loads of different levels.
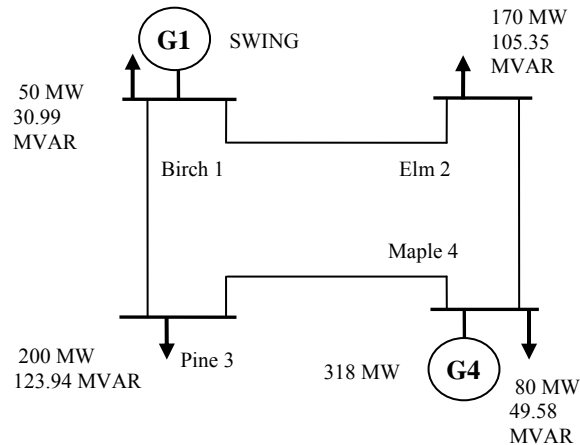


Figure 4. Four bus system network.

### 5.2. Results
Using Fast Decoupled Method load-flow analysis for the four bus network depicted above, voltage level and angle of all buses are found from the network data given in Table 1. For each load-bus (bus 2 and 3), desired voltage raise, $\Delta V$ is calculated from subtracting the base case voltage from the target voltage 1.0 p.u. Capacitor bank size is then determined by the proposed method. A test load-flow is run to find the new voltage level after installing the calculated capacitor bank. Then in traditional way, load-flow analysis is run several times to find the actual capacitor bank size. The bar chart shows the details graphical comparison between two methods in figure 5 and figure 6.

Table 1. Line Data of the 4-Bus System Network

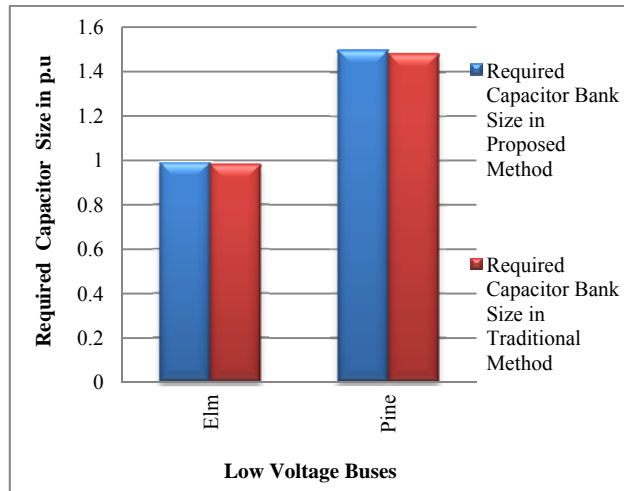| Line | Series Impedance Z | | Shunt Admittance Y |
|---|---|---|---|
| Bus to Bus | Resistance/R in p.u. | Reactance/X in p.u. | Y/2  in p.u. |
| 1-2 | 0.01008 | 0.0504 | 0.05125 |
| 1-3 | 0.00744 | 0.0372 | 0.03875 |
| 2-4 | 0.00744 | 0.0372 | 0.03875 |
| 3-4 | 0.01272 | 0.0636 | 0.06175 |

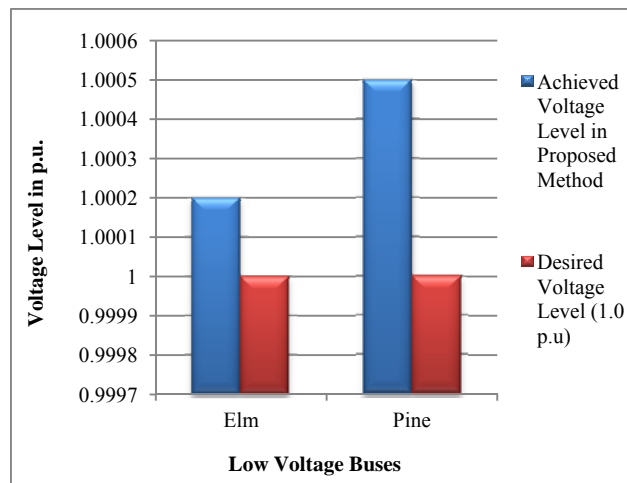Figure 5. Relative comparison between traditional and proposed method for determining the capacitor bank



Figure 6. Comparison between desired (1.0 p.u.) and achieved voltage level by proposed method in 7-bus network

So it has been observed that our proposed method works quite successfully for the four-bus system. The method works perfectly for the simplicity of the network which consists of two generator-buses and only two load-buses. The generator buses are able to meet the reactive power demand of the load buses. So voltage level deteriorates a little. As voltage level deteriorates a little for the four bus system, a more complex network needs to be analyzed to verify the validity of our proposed method of computation.

## 6.   CONCLUSION

To maintain the system reliability it is necessary to compensate the reactive power and thereby the selection of reactor (capacitor or inductor) bank is required. This work is solely devoted to develop a fast and simple algorithm for the computation of capacitor and inductor bank size for static VAR compensator. In traditional method several trials and errors are to be done each of which comprises several iterations which make this method complicated and time consuming, whereas the proposed method of computation needs a trivial computation which is less time consuming and simple. It is very tough to implement the time consuming and complicated traditional method for online capacitor or inductor bank computing purpose. On the other hand, being extremely fast, the proposed method of computation has high opportunities to be used for online capacitor or inductor bank computation purpose. In case of addition of new buses or some modification of the system, the $Z_{bus}$ can be modified easily using certain procedures. In case of reactive power compensation of two or more buses at a time with the proposed method of computaion, the method is

to be applied on the buses one by one. After applying the method once in one of the buses, a test load-flow is to be run to observe the effect on the voltages. These new voltages are to be taken in account while applying the method on the next bus. The $Z_{bus}$ of a network during faults differs from the $Z_{bus}$ in steady state as sub transient reactance of generators is included. For simplicity, it is avoided during the development of the proposed method of compution. Further work needs to be done to modify the proposed method of computaiton by analyzing the system taking transient and sub-transient reactance in account. While developing the theory, the load current of the circuit is ignored, this can cause some effect on the desired result. The proposed method of computaiton is a simple and uncomplicated method for analyzing the power flow and reactive power compensation of complicated power system network having many buses.

## REFERENCES

[1] Md Imran Azim and Md Fayzur Rahman, "Genetic Algorithm Based Reactive Power Management by SVC", *International Journal of Electrical and Computer Engineering (IJECE)* ISSN: 2088-8708, Vol. 4, No. 2, April 2014, pp. 200~206

[2] Poornima Pankajam T, J Srinivasa Rao, and J Amarnath, "ATC Enhancement with FACTS Devices Considering Reactive Power Flows Using PTDF", *International Journal of Electrical and Computer Engineering (IJECE)* ISSN: 2088-8708, Vol. 3, No. 6, December 2013, pp. 741~750

[3] Ashfaq Husain, Electrical Power Systems, 5th Edition, CBS Publisher, New Delhi, India 2007.

[4] Ramasamy Natarajan, Power System Capacitors, Taylor & Francis group, 2005.

[5] John J Grainger, William D Stevenson, Power System Analysis, Tata McGraw Hill, New Delhi, India 2003.

[6] Stott B and O Alsac, "Fast Decoupled Load Flow", *IEEE Transactions on Power Apparatus & Systems*, Vol. PAS-93, pp. 859–869. 1974.

[7] Arthur R Bergen, Vijay Vittal, Power system analysis, 2nd Edition, Pearson, 1999.

[8] BM Weedy , Electric Power System, John Wiley & Sons, Great Britain, 1972

[9] VK Mehta and Rohit Mehta, Principles of Power Systems, 4th Revised Edition, S. CHAND, New Delhi, India, 2011

[10] Fabio Saccomanno, Electric Power Systems: analysis and control, John Wiley & Sons, U.S, 2003.

[11] J Duncan Glover, Mulukutla S Sarma and Thomas J Overbye, Power System Analysis and Design, 4th Edition, Thomas Learning, Ontario, Canada, 2008

[12] Debapriya Das, Electrical Power Systems, New Age International (P) Ltd., Publishers, New Delhi, India, 2006.

## BIOGRAPHIES OF AUTHORS

Md. Ruhul Amin has been working as a Lecturer at the Department of Electrical and Electronic Engineering in the University of Information Technology & Sciences (UITS), Dhaka, Bangladesh since January 2013. He holds a Bachelor of Science degree in Electrical and Electronic Engineering with specialization on Power Systems Engineering from UITS'2012, Dhaka. He has a number of papers in national and international journals and conference in his area of expertise. His research area addresses the issues related to Electrical Power System and Engineering; FACTS, Distributed Generation and Control; HVDC; Renewable Energy; Smart Grid; Power Electronics.

Rajib Baran Roy is currently working as an Assistant Professor in the Electrical and Electronic Engineering department of the University of Information Technology and Sciences (UITS), Dhaka, Bangladesh. He has completed Bachelor of Science in Electrical Electronic Engineering from Chittagong University of Engineering and Technology (CUET), Chittagong, Bangladesh and Master's of Science in Sustainable Energy System and Management from University of Flensburg, Germany. So far he has five publications in international journals. His research interests are electrical power system analysis, reactive power compensation, hybrid power system, and renewable energy based distributed power system and application of industrial electronics in power system.