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Optimal Reactive Power Control for Distribution Network Loss Reduction

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Abstract
This paper presents, genetic algorithm based centralized control method to get optimal voltage at load buses and realize reactive power control. In this study 24 hours day ahead coordination among the on load tap changers (OLTC) and Switched capacitors (SC) is shown based on forecasted load profile for the next day. The objective is to determine the optimal 24 hours period schedule for switching of OLTC and SCs with the goal to minimize power loss restricting the voltage profile within an acceptable band and limiting the switching operations of the components such as to increase their life expectancy. The usefulness of the proposed technique is tested through the simulation of modified IEEE-10 bus test distribution network. After coordinating all the control devices, it was found that the voltage profile can be improved and the number of tap operations for OLTC can also be reduced.

Keywords
Reactive power control — Switching schedule — On load Tap Changers — Switched Capacitor

1. Introduction

Reduction of I^2R loss in an electrical power distribution network improves the overall efficiency of the network. The I^2R loss can be separated into two parts based on active and reactive components of branch currents Switched Capacitor (SC) not only reduces the loss associated with reactive component of branch current but also improves power factor and stability. Addition of shunt capacitors can generate the reactive power and therefore it is not necessary to supply all reactive power demands and losses by the source consequently the voltage profile will improve. An Automatic voltage regulator is usually installed to control the secondary bus voltage of main transformer at distribution substation through the action of transformer on load tap changers (OLTC). Consumers located at the downstream side of network are more prone to voltage drop. In such scenarios OLTCs are likely to raise the voltage on secondary side of the transformer by changing the tap to an appropriate level. OLTC is normally provided with a LDC feature built in it. In practice, the LDC function is disabled to keep the operation simplified. Independent operation of OLTC and SC may cause frequent tap change operations. Tap Change or the switching of OLTC or SC is counted as number of operations which impacts the lifetime of the device. A voltage regulating device with less tap changes during its operations would have longer lifetime, making the Volt/Var control scheme more efficient. Capacitor switching affects secondary bus voltage of the transformer and hence may cause more often tap change operations to take place which eventually result in decreased life expectancy of OLTC and higher maintenance cost [1, 2, 3].

In a conventional distribution network, heavy load causes the consumers far away from the substation suffer under-voltage violation. Raising the source voltage fixes the problem but causes over-voltage violation under light load [4]. There are three different control modes for the tap change operation, i.e. the manual control mode (MANU mode), the automatic control mode (AUTO mode), and the reactive power device control mode (RPDC mode). In the manual control mode, the operators are directly in charge of the dispatch of OLTC and SC. The MANU mode is employed in situations where the operators' judgments and decisions in reactive power/voltage control are required. In the automatic control mode, the tap position of the OLTC is changed by the automatic voltage regulator which responds to the change in secondary bus voltage. But the automatic control mode has some disadvantages. Since the automatic voltage regulator and the VA controller function independently, good coordination between the OLTC control and SC on/off control is impossible. Some aged automatic voltage regulators may have delayed response to voltage deviations. Unnecessary frequent operation of the SC circuit breaker may be experienced in situations where there are temporary changes in the reactive power flow over the main transformer. Even the reactive power device control (RPDC) mode has some drawbacks during practical operation. If the number of OLTC tap position movements in a day has exceeded the maximum allowable number of switching operations (30 in the present work), the RPDC mode will be disabled when it tries to activate further change in the tap position. Therefore, it may happen that the allowable thirty switching operations are exhausted in the afternoon and it is impossible to make any tap adjustment in the future hours [5].

In summary, all of those disadvantages that happen to current practice of reactive power/voltage control in distribution substation may be avoided by the proposed approach. This paper focuses on the reduction of the number of operations of OLTC and SCs to ensure that lifetime of these devices are not adversely affected.

2. Methodology

The methodology followed in this study is summarized in flowchart depicted in Figure 1. The system shown in Figure 2, already compensated with capacitors [6] has been taken for the study. Day ahead forecasted 24 hours load profile together with network parameters was fed to the Matlab based program. Genetic Algorithm tool supplied with fitness function and constraint function was called upon which generated population of individuals. After continuous fitness evaluation of the individuals, the population evolved towards the optimal solution. Newton Raphson method has been used by Matpower 6.0 for the power flow.

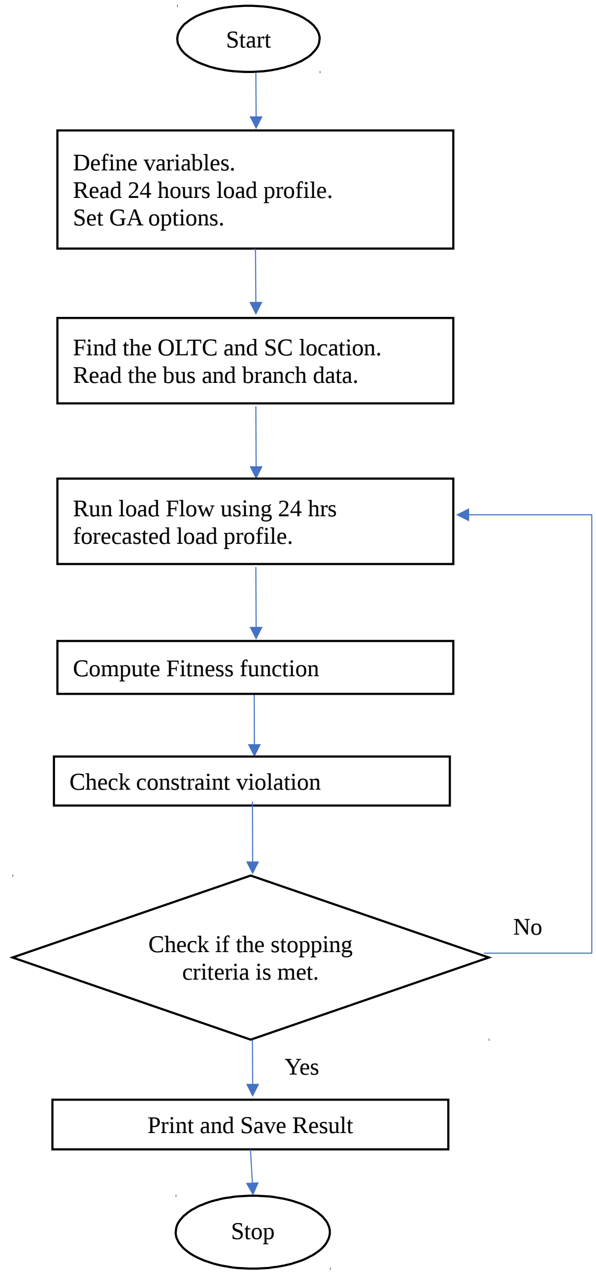

Figure 1: Flowchart of the optimization problem

3. Software and Tools

The important tool used for running the power flow is Matpower 6.0 [7] and Genetic Algorithm tool has been used for the optimization of the problem. Both the tools are based on Matlab environment and are called upon in the algorithm through appropriate codes as and when required.

4. System under study

In order to test the proposed scheme for the optimal control of voltage regulators and switched capacitors, a 23 kV IEEE 10 bus test distribution system is used. The one-line diagram of this system is shown in Figure 2.

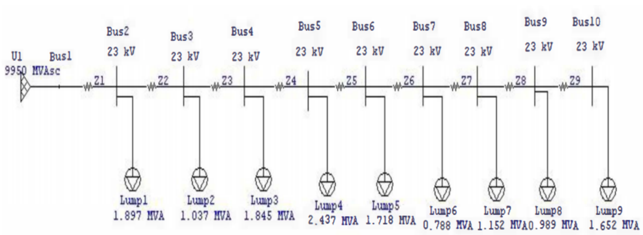

Figure 2: Single line diagram of IEEE-10 bus radial distribution system [8]

Four capacitors are installed along the feeder. Capacitor of sizes 2.1 Mvar, 1.5 Mvar, 0.45 Mvar and 0.9 Mvar have been placed at buses 2, 5, 6 and 9 respectively. For the optimization problem, the objective function will be the minimization of MW loss calculated over a 24 hour period. OLTC and SC are switched optimally for the voltage control. Voltage is controlled such that the voltage at any bus always lie within a dead band. The constraints that must be taken into account include primarily the voltage limits on the feeder and the daily maximum allowable number of switching operations in a day for the OLTC and capacitors. With the hourly forecasted Real and Reactive power demand by the loads for the next day at hand, it is desirable to determine an optimal dispatch schedule for the next 24 hours. The problem can be mathematically expressed as [1]:

$$\text{Minimize} \sum_{hr=1}^{24} \left(\sum_{br=1}^{n} Ploss \right) \tag{1}$$

Subjected to:

$$\text{Voltage Constraint, } V_j^{lb} \leq V_j \leq V_j^{ub} \tag{2}$$

$$\text{Capacitor Switch Constraint, } C_j^{lb} \leq C_j \leq C_j^{ub} \tag{3}$$

$$\text{Tap Change Constraint, } T_j^{lb} \leq T_j \leq T_j^{ub} \tag{4}$$

Where $n =$ number of feeder branches
$V_j^{lb} = 0.90$ and $V_j^{ub} = 1.10$
$C_j^{lb} = 0$ and $C_j^{ub} = k\,(k = 1, 2, 4)$
$T_j^{lb} = 0$ and $T_j^{ub} = 30$

As there are four capacitors in the test network, for each capacitor the solution must contain 24 values representing the 24-hour status. In total $4 \times 24 = 96$ variables for capacitors are required. When OLTC is taken into account, 24 variables for OLTC are also required as we have only one OLTC in the test system. The concatenation of $96 + 24 = 120$ integer variables is required in the solution string. The evaluation of objective function depends on the variables generated by the GA which need to be decoded for Fitness calculation. Variables for capacitor do not need to be decoded as they can only be 0 or 1 representing 'ON' or 'OFF' status. For the OLTC as a 16 tap transformer, the value generated by the GA can be any integer T between -8 to $+8$. This integer value is then decoded using the equation, $tap = 1 \pm 0.0125 \times T$ for fitness. For each individual of the population created, Matlab runs the power flow.

5. Results and Discussions

The initial voltage profile of the network when there was no voltage regulator or capacitors is shown in Figure 3.

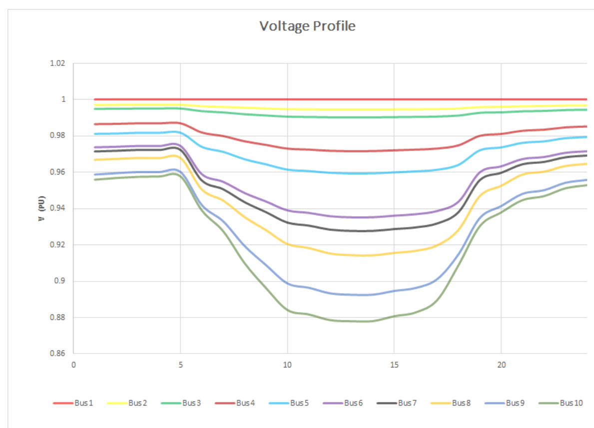

Figure 3: Voltage Profile of the feeder without volt/var control

For a particular load profile, six cases were studied, the maximum number of switching operations of capacitors in a day was limited to one, two and four respectively for scenarios with and without the presence of tap changers. For each case GA was run to obtain the optimal switching schedule and the corresponding voltage profile of the feeder was observed.

Case 1:

Table 1: Schedule for capacitor switch limit = 1

Hour	C1	C2	C3	C4
1	0	1	1	1
2	0	1	1	1
3	0	1	1	1
4	0	1	1	1
5	0	1	1	1
6	1	1	1	1
7	1	1	1	1
8	1	1	1	1
9	1	1	1	1
10	1	1	1	1
11	1	1	1	1
12	1	1	1	1
13	1	0	1	1
14	1	0	1	1
15	1	0	1	1
16	1	0	1	1
17	1	0	1	1
18	1	0	1	1
19	1	0	1	0
20	1	0	1	0
21	1	0	1	0
22	1	0	1	0
23	1	0	0	0
24	1	0	0	0
Number of change	1	1	1	1

Case 2:

Table 2: Schedule for capacitor switch limit = 2

Hour	C1	C2	C3	C4
1	0	1	1	1
2	0	1	1	1
3	0	1	1	0
4	0	1	1	0
5	0	0	1	0
6	0	0	1	0
7	0	0	1	1
8	0	0	1	1
9	0	0	1	1
10	0	1	1	1
11	1	1	1	1
12	1	1	1	1
13	1	1	1	1
14	1	1	1	1
15	1	1	1	1
16	0	1	1	1
17	0	1	1	1
18	0	1	1	1
19	0	1	1	1
20	0	1	1	1
21	0	1	1	1
22	0	1	1	1
23	0	1	1	1
24	0	1	1	1
Number of change	2	2	0	2

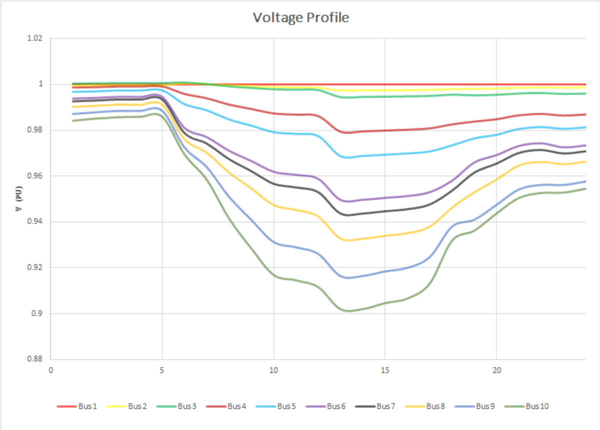

Figure 4: Voltage profile for capacitor switch limit = 1

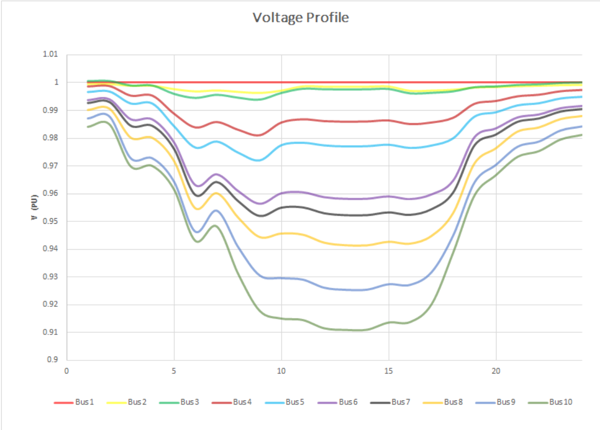

Figure 5: Voltage profile for capacitor switch limit = 2

Case 3:

Table 3: Schedule for capacitor switch limit = 4

Hour	C1	C2	C3	C4
1	1	1	0	0
2	0	1	0	0
3	0	1	0	0
4	0	1	0	0
5	0	1	1	0
6	0	1	1	0
7	1	1	1	0
8	1	1	1	0
9	1	1	1	0
10	1	1	1	1
11	1	1	1	1
12	1	1	0	1
13	1	1	1	1
14	1	1	1	1
15	1	1	1	1
16	1	1	1	1
17	1	1	1	1
18	1	1	1	0
19	1	1	1	0
20	1	1	1	0
21	0	1	1	0
22	1	1	0	0
23	1	1	0	0
24	1	1	0	0
Number of change	4	0	4	2

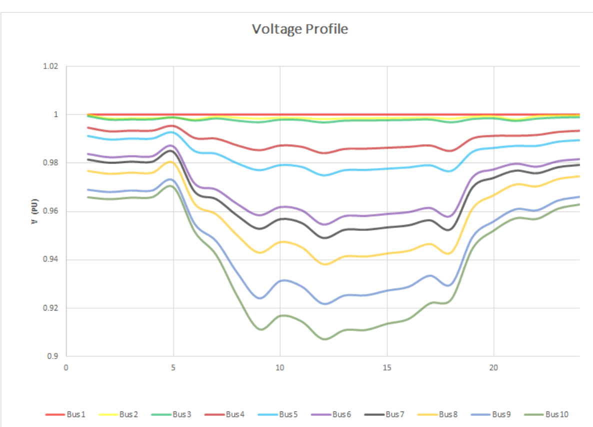

Figure 6: Voltage profile for capacitor switch limit = 4

Case 4:

Table 4: Schedule for capacitor switch limit =1, tap change limit = 30

Hour	C1	C2	C3	C4	Tap
1	1	1	0	1	-7
2	1	1	1	1	-7
3	1	1	1	1	-7
4	1	1	1	1	-7
5	1	1	1	1	-7
6	1	1	1	1	-7
7	1	1	1	1	-7
8	1	1	1	1	-7
9	1	1	1	1	-7
10	1	1	1	1	-7
11	0	1	1	1	-7
12	0	1	1	1	-7
13	0	1	1	1	-7
14	0	1	1	1	-7
15	0	1	1	1	-7
16	0	1	1	1	-7
17	0	1	1	1	-7
18	0	1	1	1	-7
19	0	0	1	0	-7
20	0	0	1	0	-7
21	0	0	1	0	-7
22	0	0	1	0	-7
23	0	0	1	0	-7
24	0	0	1	0	-7
Number of change	1	1	1	1	0

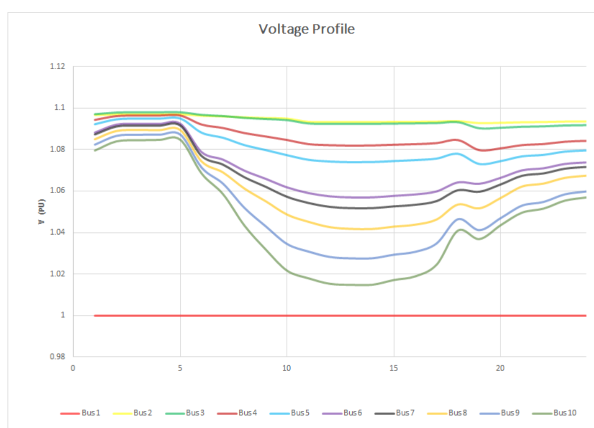

Figure 7: Voltage profile for capacitor switch limit =1, tap change limit=30

Case 5:

Table 5: Schedule for capacitor switch limit =2, tap change limit = 30

Hour	C1	C2	C3	C4	Tap
1	1	0	1	0	-7
2	1	0	1	0	-7
3	1	0	1	0	-7
4	1	0	1	0	-7
5	1	0	1	0	-7
6	1	1	1	0	-7
7	1	1	1	0	-7
8	1	1	1	0	-7
9	1	1	1	0	-7
10	1	1	1	0	-7
11	1	1	1	0	-7
12	1	1	1	0	-7
13	1	1	1	0	-7
14	0	1	1	0	-7
15	0	1	1	0	-7
16	0	1	1	0	-7
17	0	1	1	0	-7
18	0	1	1	0	-7
19	0	1	0	0	-7
20	0	1	0	0	-7
21	0	1	0	1	-7
22	1	0	0	1	-7
23	1	0	0	1	-7
24	1	0	0	1	-7
Number of change	2	2	1	1	0

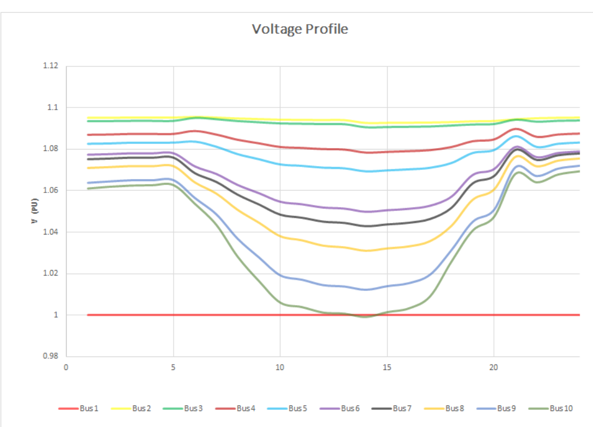

Figure 8: Voltage profile for capacitor switch limit =2, tap change limit=30

Case 6:

Table 6: Schedule for capacitor switch limit =4, tap change limit = 30

Hour	C1	C2	C3	C4	Tap
1	0	0	0	1	-7
2	0	0	0	1	-7
3	1	0	0	1	-7
4	1	0	0	1	-7
5	1	1	0	1	-7
6	1	1	0	1	-7
7	0	1	0	1	-7
8	0	1	0	1	-7
9	0	1	1	1	-7
10	0	1	1	1	-7
11	0	1	1	0	-7
12	0	1	1	0	-7
13	0	1	1	0	-7
14	0	1	1	0	-7
15	0	1	1	0	-7
16	0	1	1	1	-7
17	0	1	0	1	-7
18	1	1	0	1	-7
19	1	1	0	1	-7
20	1	0	0	1	-7
21	1	1	1	0	-7
22	1	0	1	1	-7
23	0	0	1	1	-7
24	0	0	1	1	-7
Number of change	4	4	3	4	0

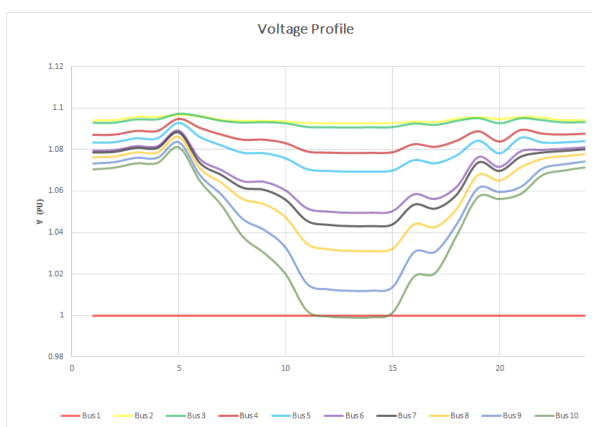

Figure 9: Voltage profile for capacitor switch limit =4, tap change limit=30

The losses and maximum and minimum voltage for every cases is listed below:

Table 7: Comparative analysis of scenarios with and without control

Case	Eloss (MWh)	Vmin (pu)	Vmax (pu)
Without capacitor and OLTC	5.5413	0.8779	1
With unregulated capacitor	5.1892	0.9111	1.0023
With capacitor control in absence of OLTC			
Capacitor switch limit =1	5.1502	0.9021	1.0009
Capacitor switch limit =2	5.0353	0.9111	1.0005
Capacitor switch limit =4	4.9166	0.9073	1.0001
With constrained OLTC and capacitor control			
Capacitor switch limit =1, tap change limit=30	4.1507	1.015	1.098
Capacitor switch limit =2, tap change limit=30	4.0881	0.9992	1.0957
Capacitor switch limit =4, tap change limit=30	4.0545	0.9997	1.0942

Hence, it was observed that after the implementation of genetic algorithm for minimizing the feeder loss such that the voltage limits and switching limits for a day was not violated, the switching schedule for capacitors and tap changing transformer was obtained. The energy loss of the feeder when there were no OLTC and capacitors in the distribution line was 5.5413 MWh, the voltage dropping to as low as 0.8779 pu. On addition of tap changer and capacitors of size 2.1 MVar, 1.5 MVar, 0.45 MVar and 0.9 MVar at buses 2, 5, 6 and 9 the network losses dropped significantly. Presence of fixed capacitors at the nodes mentioned above would reduce the losses to 5.1892 MWh with a slight improvement in the observed minimum voltage (0.9111) lifting the node voltage to lie within the deviation band of ± 10 %. When switched capacitors were used alone, the feeder losses happened to reduce more. The capacitor switching limit in a day was varied as 1, 2 and 4 and the corresponding value of losses and voltage range was compared. It was observed that when the capacitor switching limit was set as 1, 2 and 4, the line losses accounted to 5.1502 MWh, 5.0353 MWh and 4.9166 MWh respectively satisfying voltage boundaries. Further, when switched capacitors were used along with OLTC, the feeder losses reduced even more. Fixing the tap changers to a maximum operation of 30 per day, the capacitor switching limit in a day was varied as 1, 2 and 4 and the network loss yielded to 4.1507 MWh, 4.0881 MWh and 4.0545 MWh respectively voltage lying within ± 10 % of specified value. It can be derived that on moving from unregulated capacitors to regulated ones without transformer OLTC and ultimatey to regulated capacitors with transformer OLTC, the line losses was found to decrease significantly. With increasing switching operations, the feeder losses was observed to be decreasing. In addition, the additional feeder loss reduction that can be achieved is very insignificant when maximum number of switching operation exceeds 2 ($k > 2$). With capacitor switching limit set at 1 and further increasing switching limit to 2, the MWh saving achieved in network losses increased at a greater rate but when switching limit was further increased to 4, the saving in losses increased at significantly lower rate. As frequency of switching operations may decrease the life expectancy of the control components and may cause transient voltages on the feeder, it seems proper to allow the capacitors to be switched twice a day at most for the system under study.

6. Conclusion

An approach based on genetic algorithm has been developed to determine the optimal dispatching schedule for capacitors and OLTC on a distribution feeder in daily system operation. It is found that the total feeder losses in the study period (24hours) can be reduced if the capacitors and OLTC are dispatched according to the schedule achieved in this work. Another feature of the proposed method is that the number of switching operations in a day for each capacitor bank is limited, owing to the practical consideration of their life expectancies. In the present work, only four capacitors are present on feeder, and the computational complexity of the proposed approach depends mainly on the number of switchable components on the feeder. The topology of the feeder and locations of the switchable capacitors affect the solution time in computing the network losses. If there are a great number of capacitors, some simplifying procedures must be employed to reduce the CPU time.

The main challenge in optimizing with GA was tuning of GA options such as to avoid local optima. More precise solutions demand larger numbers of the population. However, larger populations tend to take more time to generate solutions consequently taking much time to reach the optimal solution.

References

[1] Ruey-Hsun Liang and Chen-Kuo Cheng. Dispatch of main transformer ultc and capacitors in a distribution system. *IEEE Transactions on Power Delivery*, 16(4):625–630, Oct 2001.

[2] M. H. Haque. Capacitor placement in radial distribution systems for loss reduction. *IEE Proceedings - Generation, Transmission and Distribution*, 146(5):501–505, Sep 1999.

[3] Mats Larsson. *Coordinated Voltage Control in Electric Power Systems*. PhD thesis, Lund University, 2001.

[4] Yue Shi et al. An investigation of volt/var control on freedm systems. 2014.

[5] F.-C. Lu. Reactive power/voltage control in a distribution substation using dynamic programming. *IEE Proceedings - Generation, Transmission and Distribution*, 142:639–645(6), November 1995.

[6] P. Kumar, A. K. Singh, and N. Singh. Sensitivity based capacitor placement: A comparative study. In *2011 6th International Conference on Industrial and Information Systems*, pages 381–385, Aug 2011.

[7] Ray Daniel Zimmerman, Carlos Edmundo Murillo-Sánchez, and Robert John Thomas. Matpower: Steady-state operations, planning, and analysis tools for power systems research and education. *IEEE Transactions on power systems*, 26(1):12–19, 2011.

[8] A. Kumar and R. S. Bhatia. Optimal capacitor placement in radial distribution system. In *2014 IEEE 6th India International Conference on Power Electronics (IICPE)*, pages 1–6, Dec 2014.