Optimal Voltage Restoration in Electric Power System Using Genetic Algorithms

A. Ulinuha, S.M. Islam, *Senior Member, IEEE*, and M.A.S. Masoum, *Senior Member, IEEE*

Abstract--**The optimal voltage restoration and loss minimization in distribution system using Genetic Algorithms (GAs) is presented. The optimization is carried out by scheduling Load Tap Changer (LTC) and shunt capacitors to simultaneously improve the voltage and minimize the energy loss. Two GAs are developed to determine the load interval division and the optimal schedule of the controllable devices, respectively. Encoding ability of the proposed method enables checking the fulfillment of switching constraints of any possible schedule prior to performing calculations. This will significantly reduce the computation burden due to unnecessary calculations for infeasible schedules. The optimization is performed for the IEEE 123-bus distribution system. The generated results indicate that the developed methods are effective for the optimal scheduling problem by providing voltage improvement and energy loss minimization.**

Index Terms--**Energy loss, Genetic Algorithms, loss reduction, LTC and shunt capacitors, voltage improvement.**

I. Introduction

THE operation planning of a distribution system is aimed to assure that electrical loads can be continuously satisfied in an optimum way. The constantly changing loads make the planning very complicated that may lead to less chance of success in achieving this aim. Load variations may cause several problems in distribution system, such as voltage violation and power loss escalation. Adaptable enhancement approaches may be required for voltage restoration as well as loss reduction. This essentially comes down to the scheduling of controllable devices in distribution system such as Load Tap Changer (LTC) and switched shunt capacitors for preventing voltage violation and power loss escalation while satisfying the constraints.

LTC is employed to control substation secondary voltage such that the voltage along distribution feeders can be maintained close to the preset value under changing load conditions. However, regulating the voltage at this way does not improve the voltage profile over the feeders but simply sets the voltage level by shifting the voltage up or down. Therefore, shunt capacitors are then installed in distribution system to provide reactive power compensation such that the voltage profile along the feeders is maintained within acceptable limits and the power loss is minimized. However, these capacitors need to be switched out during the light load conditions.

The use of LTC alone cannot completely improve the voltage profile and requires the use of shunt capacitors for further voltage improvement. On the other hand, the reduction of power loss due to switching of shunt capacitors will be further enhanced by voltage improvement because of LTC operation. This highlights the necessary of simultaneous and proper coordination of the switched devices for significant voltage profile improvement and power loss reduction. Unfortunately, comprehensively taking the controlled devices into account may lead the optimization problem to be very complicated.

The optimal scheduling of LTC and shunt capacitors for voltage restoration and power loss minimization is a multi-phase decision-making problem with discrete variables and nonlinear objective function [1]. The value of objective function is determined from power flow solutions given the settings of the control variables. Additionally, it is desirable to obtain this objective value in the least possible number of control steps. The relation between bus voltage and control variables, which is highly nonlinear makes the problem quite complicated [2]. The interdependence between bus voltage and capacitor setting will complicate the problem even further. Problem dimension is another difficulty that results in heavy computation burden. The maximum switching limitation of the controlled devices [3] will further lead the computation to be very intense as this constraint can only be confirmed after evaluating all states over the study period. On the other hand, simplifying the problem will severely reduce the optimization benefits. These emphasize the important of effectively solving the complicated problem without reducing the solution accuracy. Choosing the most suitable method is therefore needed to achieve this purpose.

In this paper, two Genetic Algorithms (GAs) are developed and employed to effectively solve the optimization problem. The first GA is developed to accurately divide the load curve into a number of partitions. With the proper load intervals in hand, the hourly schedule of the controllable devices can be determined using the second GA. For the optimal scheduling purpose, GA is selected due mainly to its ability for simultaneously involving the switching elements in dispatch scheduling and checking the fulfillment of switching

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constraints prior to performing calculation for any possible schedule. This will greatly reduce the computational burden by avoiding calculation for the ineligible solutions. The effectiveness of the developed methods is verified in their applications for the IEEE 123-bus distribution system.

II. Problem Description

The objective function of optimal scheduling of the controllable devices is minimization of energy loss over 24-hour period.

$$E = \min \sum_{t=1}^{24} P_{loss}(Q_t, T_t) * \Delta t \quad (1)$$

Where E is the minimum energy loss, P_{loss} is total power loss at hour t as a function of Q_t and T_t that are the status of shunt capacitors and tap position of LTC, respectively. While, Δt is time interval that is normally taken as 1 hour. This objective function is subject to the following constraints:

1. Voltage constraint

$$V_{i\min} \le V_i \le V_{i\max} \quad (2)$$

Where $V_{i\min}$ and $V_{i\max}$ are the respective minimum and maximum limits of voltage at bus i (V_i).

2. Maximum switching operation of LTC

$$\sum_{t=1}^{24} \left| TAP_t - TAP_{t-1} \right| \le K_T \quad (3)$$

Where TAP_t and K_T are LTC tap position at hour t and the allowed maximum LTC switching, respectively.

3. Maximum switching operation of shunt capacitors

$$\sum_{t=1}^{24} \left(X_{ct} \oplus X_{ct-1} \right) \le K_C \; ; c = 1, 2, \ldots, nc \quad (4)$$

Where X_{ct} and K_c are the status of capacitor c at hour t and the maximum switching allowed, respectively. While nc is the number of shunt capacitors installed.

III. Solution Proposed

The interdependence between bus voltages and capacitor settings makes the optimization problem quite complicated. The switching effect of shunt capacitors on secondary bus voltage may change LTC tap position resulting in frequent LTC operation. It may reduce LTC lifetime and higher maintenance cost. Some simplifications to avoid this oscillation have been proposed, such as independent operation of LTC and shunt capacitors to separately control secondary bus voltage and reactive power [4] and determination of capacitors switching status prior to LTC tap status [5-9]. Unfortunately, these simplifications may severely reduce the optimization benefits. Problem dimension is another difficulty that leads the optimization to encounter "dimensional exploration disaster" [10]. The maximum switching limitation of control devices makes the computation very intense, as this constraint can only be confirmed after evaluating all states over the study period [3].

The aforementioned difficulties highlight the necessity of solving the problem effectively without reducing the solution accuracy. The interdependence between capacitor switching and LTC tap movement requires a simultaneous control of these switched elements. The problem that has very big dimension can be effectively taken in hand by employing the most suitable technique. To effectively satisfying the maximum allowable LTC switching, the daily load curve can be divided into several intervals [11]. The optimal intervals determination should be effectively carried out by the technique chosen. The selected technique should also be capable to provide the possibility of checking the switching constraints of any possible schedule prior to calculating it. These will greatly reduce the computational burden due to unnecessary calculations for the unfeasible schedules.

According to the abovementioned considerations, Genetic Algorithm (GA) is therefore proposed for the problem mentioned above. In addition to its general features, GA is justified due mainly to its encoding ability that enables comprehensively considering simultaneous schedule of LTC and shunt capacitors, and to check the switching constraints before performing any calculations.

IV. The Implementations of Genetic Algorithms

Genetic Algorithm is robust and able to find near global optimal solution as it performs multi-directional search. It is especially effective in finding solution to the problems for which other optimization techniques encounter difficulties. It belongs to the class of probability, but it is different from random algorithms as it combines elements of directed search by maintaining a population of potential solution. However, the disadvantage of this algorithm is the high processing time associated.

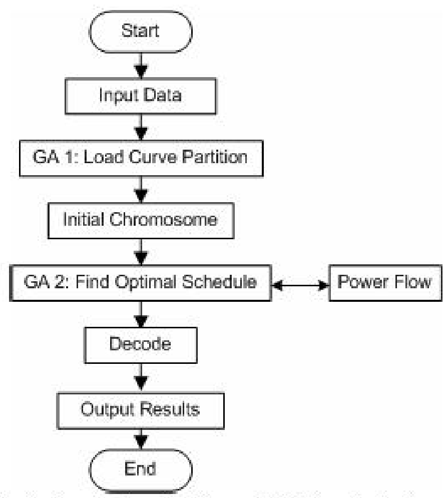

Fig. 1. Flowchart of optimal scheduling of LTC and shunt capacitors for voltage restoration and power loss reduction using Genetic Algorithms.

GA is initially constituted by a population randomly generated and followed by a cycle of three stages: evaluation of each chromosome in the population, selection of chromosomes for reproduction and genetic manipulation to create a new population, which includes crossover and mutation. Completing this cycle means that one generation has occurred. After some number of generations, the program converges and the best individual represents a reasonably optimal solution. In this paper, two GAs are developed and employed for determination of optimal load interval division and optimal dispatch schedule of the controllable devices. The flowchart of the optimization calculations is shown in Fig. 1.

A. Load Interval Division

The idea of load interval division is based on the reality that several apparent load levels exist during a day. These intervals can therefore be used to determine the LTC tap position; which remains constant during a load interval and may differ at a different load interval. A typical load curve [12] is shown in Fig. 2 and will be used in this paper.

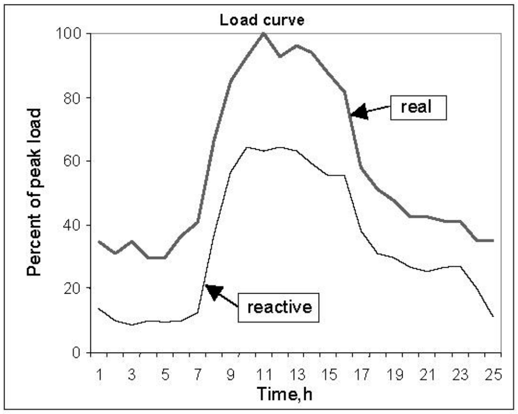

Fig. 2. A typical daily load curve [12].

If the intervals of load can be properly determined, the schedule of LTC tap position can be effectively decided. This will not only take into account the overall daily load change, but also easily satisfy the LTC switching constraint. With an accurate result of load forecasting in hand, the LTC dispatch obtained in this way can be practically implemented.

In order to determine the optimal load intervals, the number of interval is initially assumed. GA is then employed to determine the start and end of each interval. The chromosome of GA is therefore constructed to represent the possible interval combination and is then evaluated by the following fitness function [11].

$$F = F_{\max} - \min \sum_{l=1}^{L} \sum_{t=1}^{T} \left[(P_{tl} - PA_l)^2 + (Q_{tl} - QA_l)^2 \right] \qquad (5)$$

Subject to

$$\sum_{l=1}^{L} T = 24 \qquad (6)$$

Where F_{max} is constant that converts fitness function to standard form, P_{tl} and Q_{tl} are active and reactive load at t^{th} hour of the l^{th} load interval, PA_l and QA_l are average active and reactive load at l^{th} load interval. T is number of hour at l^{th} load interval and L is number of interval for the whole load period.

B. Scheduling of LTC and shunt capacitors

The chromosome of GA that represents possible dispatch schedule of LTC and shunt capacitors can be consecutively constructed by sub chromosomes that respectively represent the switching schedule of LTC, substation capacitors and feeder capacitors [13]. Every chromosome at each generation is evaluated by the following fitness function.

$$F = \max \left[F_{\max} - \left(we \sum_{t=1}^{24} loss_t + wv \sum_{t=1}^{24} \sum_{i=1}^{I} \Delta V_{it} \right) \right] \qquad (7)$$

Where ***we*** and ***wv*** are weighting function for real power loss and voltage deviation, respectively. It should be noted, that evaluation of every single chromosome using the abovementioned fitness function requires running power flow calculation for 24 times. This however will lead to the high computation charge.

V. Results and Discussion

A. The Evolutionary Strategy of GA

The initial chromosomes are randomly generated and selected for constructing the initial population. The chromosomes chosen are those, which satisfy the switching constraints. The selection of parent for crossover uses tournament method and the children are generated by one-point crossover from their parents. The probability of crossover and mutation are fixed throughout the generation as well as the weighting coefficients. The size of population is fixed during the calculation and the best chromosome in every generation is saved and transferred directly to the next generation.

The simulation is performed for an initial population of 30 chromosomes and the number of generation is set to 50. The maximum and minimum voltage limits at every bus are 1.05 and 0.95 per-unit, respectively. The allowable maximum switching operation of LTC is 30, while the maximum switching allowed for shunt capacitors on substation and on the feeder are 6 and 2, respectively. The simulation program is coded using MATLAB version 7.0.1 R14 and is run in a desktop PC with Pentium 4 Intel 3.0 GHz processor and 512 MB RAM.

B. The SystemData

The IEEE 123-bus distribution system [14] (Fig. 3) with the addition of 14 shunt capacitor banks [15] (Table I) is used for simulation. The peak of both real and reactive loads are assumed to change according to the curve indicated in Fig. 2. As the load model has a great influence on the power flow results, this paper models the load at each bus consisting of 50% constant impedance and 50% constant power.

TABLE I
THE SHUNT CAPACITOR DATA FOR THE IEEE 123-BUS SYSTEM (FIG..3)

Capacitor	Bus Location	kVar
C1	1	50
C2	1	50
C3	13	50
C4	18	50
C5	35	50
C6	44	100
C7	57	50
C8	60	100
C9	72	50
C10	81	100
C11	86	50
C12	101	50
C13	110	100
C14	114	100

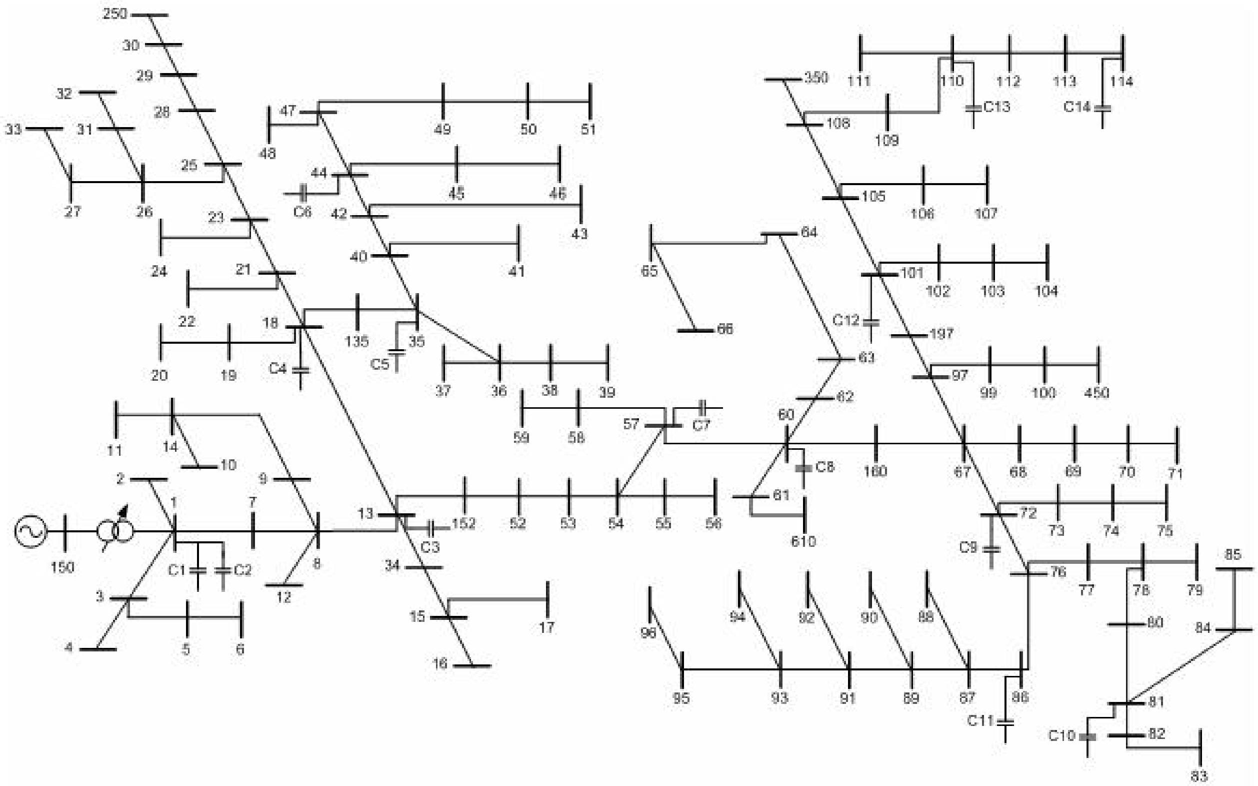

Fig. 3. The IEEE 123-bus distribution system used for simulation.

C. The Optimization Results

The optimal schedule of LTC and shunt capacitors for the IEEE 123-bus system generated by GAs is indicated in Table II. The original tap position of LTC is 0 and the initial status of all capacitors is "off" (0). Inspection of the optimal schedule indicates that all switching constraints are fully satisfied.

Observations of the optimization results confirm that the developed algorithms have successfully maintained the hourly voltage to be within the preset limits and minimized the energy loss. Bus 114 is detected to have the lowest voltage during the optimization period. Therefore, the voltage of this bus is investigated. Fig. 4 illustrates the voltage improvement of bus 114 indicating that the voltage of this bus can be improved to the acceptable level. For the uncompensated system, the voltage of the worst bus (bus 114) is lower than 89%.

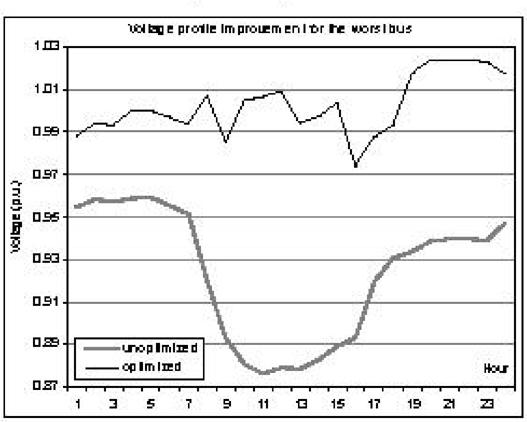

Fig. 4. The voltage improvement of the worst bus (Fig.3, bus 114).

TABLE II
OPTIMAL SCHEDULE OF LTC AND SHUNT CAPACITORS FOR THE IEEE 123-BUS SYSTEM OF FIG. 3

hour	optimal schedule														
	LTC	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14
1	2	0	0	0	0	0	0	0	0	0	0	1	1	0	0
2	2	1	0	0	0	0	0	0	0	0	0	1	1	0	0
3	2	1	0	0	0	0	0	0	0	0	0	1	1	0	0
4	2	1	1	0	0	0	0	0	0	1	0	1	1	0	0
5	2	1	1	0	0	0	0	0	0	1	0	1	1	0	0
6	2	1	1	0	0	0	0	0	0	1	0	1	1	0	0
7	2	0	1	0	0	1	0	0	0	1	0	1	1	0	0
8	5	0	1	1	1	1	1	0	0	1	0	1	1	0	0
9	5	0	1	1	1	1	1	0	0	1	0	1	1	0	0
10	5	0	0	1	1	1	1	0	1	1	1	1	1	1	0
11	5	1	1	1	0	1	1	1	1	1	1	1	1	1	0
12	5	1	1	1	0	1	1	1	1	1	1	1	1	1	0
13	5	1	1	1	0	1	1	1	1	1	1	1	1	0	0
14	5	1	0	1	0	1	1	1	1	1	1	1	1	0	0
15	5	1	1	1	0	1	1	1	1	1	1	1	1	0	0
16	3	0	1	1	0	0	1	1	1	0	1	1	1	0	0
17	3	1	1	0	0	0	1	1	0	0	1	1	1	0	0
18	3	1	1	0	0	0	1	1	0	0	1	0	1	0	0
19	5	1	1	0	0	0	0	1	0	0	1	0	1	0	0
20	5	1	1	0	0	0	0	1	0	0	1	0	1	0	0
21	5	0	1	0	0	0	0	1	0	0	1	0	1	0	0
22	5	0	1	0	0	0	0	1	0	0	1	0	1	0	0
23	5	0	1	0	0	0	0	1	0	0	1	0	1	0	0
24	5	0	0	0	0	0	0	0	0	0	0	0	1	0	0

For more illustration, the hourly average voltage regulation for the uncompensated and compensated condition is shown in Fig. 5. The average voltage regulation for the whole system before and after optimization is 5.93% and 1.38%, respectively. This generally indicates that the developed algorithms have successfully restored the voltage to be close to the preset value.

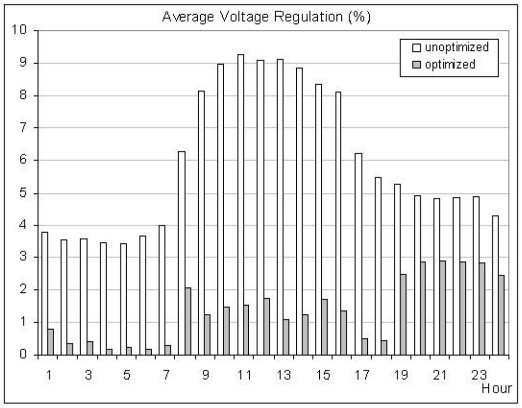

Fig. 5. Average hourly voltage regulation.

In term of loss minimization, GAs have successfully provided the optimal schedule of the controllable devices that results in real power loss minimization. The hourly real power loss reduction is shown in Fig. 6. A daily energy saving of 1019.50 kWh is achieved from this loss reduction. This verifies that the developed GAs are not only able restoring the voltage to the acceptable level, but also able minimizing the energy loss.

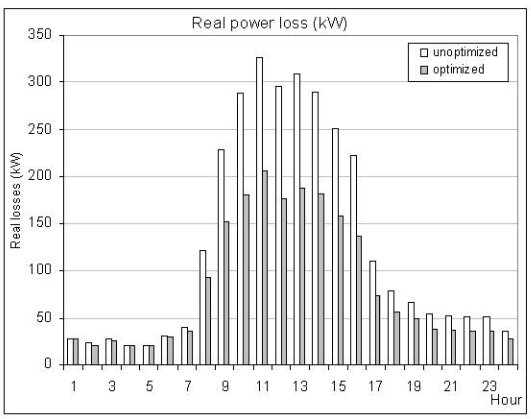

Fig. 6. Hourly real power loss reduction.

The optimization benefits are summarized in Table III indicating successful application of the developed algorithms for the problem in hand.

TABLE III
OPTIMIZATION BENEFITS FOR THE SIMULATED SYSTEM

	Uncompensated	Optimized	Benefit
Average Voltage (%)	94.07	101.03	6.96
Average Voltage Regulation (%)	5.93	1.38	4.55
Energy Losses (kWh)	3021.50	2002.00	1019.50

Table III indicates that optimal scheduling of LTC and shunt capacitors is effective in improving the voltage and minimizing the power loss. The average voltage and voltage regulation are calculated for all buses during the optimization period. This however simply provides a very rough description of voltage improvement indicated in the benefit column of Table III. The limited space does not allow displaying the complete hourly voltage as well as voltage regulation for every bus. Therefore, the bus with lowest voltage during optimization period is marked out and the voltage improvement of the related bus is then investigated. Fig. 4 indicates the acceptable voltage of the associated bus during scheduling period. This ensures that the voltage of every bus is within the specified limit during the optimization period. However the energy loss calculation has been properly carried out as the daily energy loss of the system is simply total loss of the entire bus for 24-hour period. From the obtained result, the optimization has successfully provided significant reduction of daily energy loss.

The developed Genetic Algorithms have been successfully employed for the problem in hand by providing voltage improvement and power loss minimization. On the other hand, the algorithms have exhibited the ability to optimally control the switched devices in large distribution system with a reasonable computation time. For the 123-bus distribution system, the computation time of 128.016 second is acceptable. The real distribution system normally consists of large number of bus and it is therefore necessary to develop the methods able optimizing the large practical distribution systems.

VI. CONCLUSIONS

Optimal voltage restoration and power loss minimization by optimal scheduling of LTC and shunt capacitors are carried out using Genetic Algorithms in this paper. The optimization is tested with the IEEE 123-bus distribution system resulting in the following main conclusions:

- Optimal control of LTC and shunt capacitors will enhance the distribution system operation by improving the system voltage and reducing the power loss,
- The developed Genetic Algorithms have been successfully employed for the optimal control problem by improving the voltage and minimizing the power loss,
- The developed algorithms are considered to be suitable for the problem in hand as it enables simultaneously scheduling the controllable devices and checking the fulfillment of switching constraints prior to performing unnecessary calculations, which will significantly reduce the computation time,
- For the developed Genetic Algorithms, properly constructing the fitness function and selecting the optimization parameters (such as weighting functions, number of population and generation) is expected to improve the solution even further.

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VIII. Biographies

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